United States
Department of
Agriculture

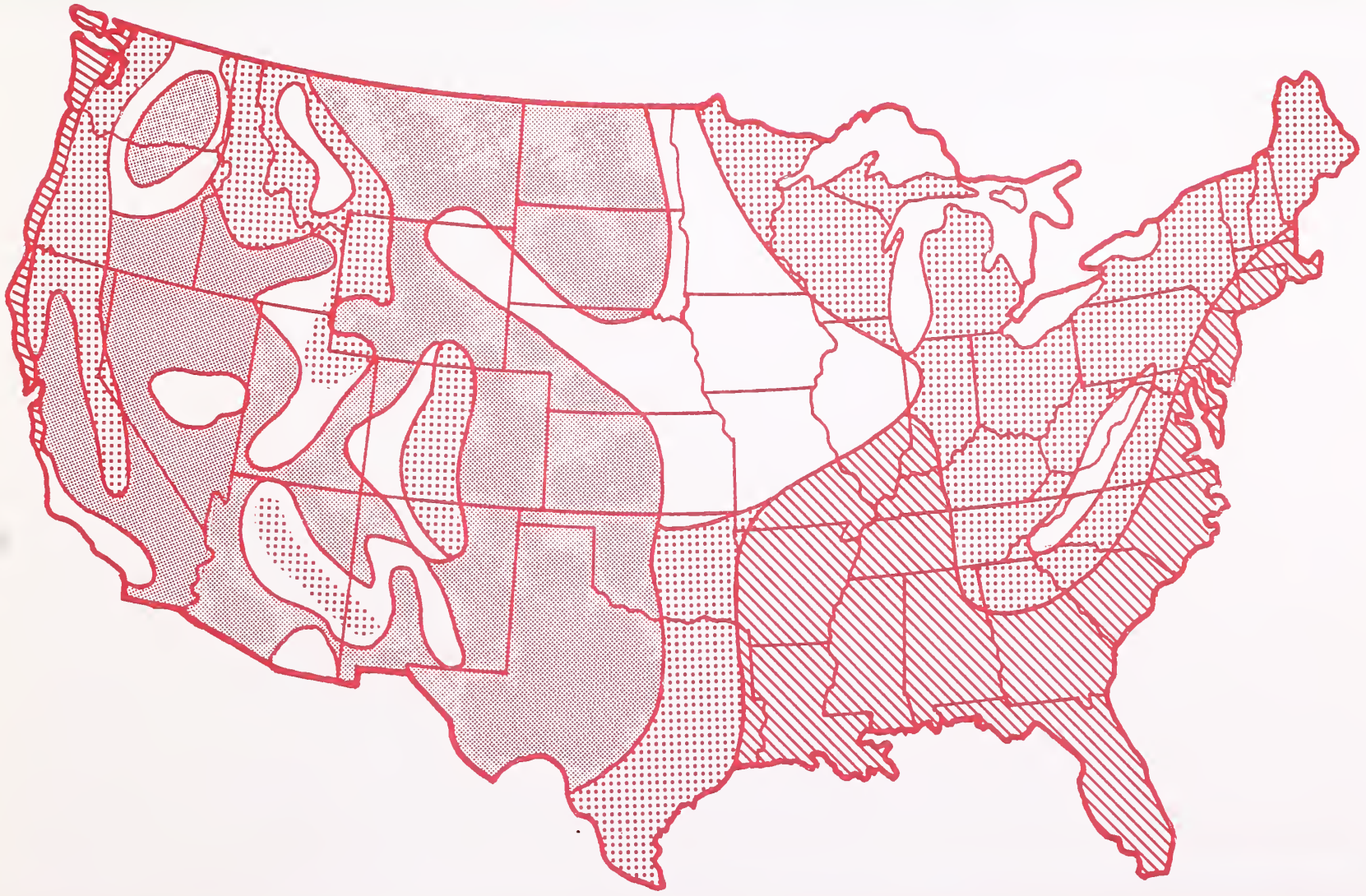
Forest Service

**Intermountain
Forest and Range
Experiment Station
Ogden, Utah 84401**

General Technical
Report INT-169

July 1983

The 1978 National Fire-Danger Rating System: Technical Documentation



COMPILERS

LARRY S. BRADSHAW is cofounder of and research meteorologist for Systems for Environmental Management (SEM), a Montana-based nonprofit research organization. He has participated in numerous cooperative studies with the Forest Service, U.S. Department of Agriculture, in the areas of fire weather, fire danger, fire behavior, and associated data management systems. Mr. Bradshaw earned his bachelor's degree in meteorology from the University of Utah.

JOHN E. DEEMING received his bachelor's degree in forestry from Utah State University in 1959 and has done graduate work in meteorology and biometeorology at the University of California at Los Angeles, the University of Hawaii, and Colorado State University. He served in the U.S. Air Force from 1960 to 1966 as a weather officer. In 1966 he joined the research staff at the Southern Forest Fire Laboratory, Macon, Ga., to work on fire control methods. Mr. Deeming transferred to the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo., in 1970. His assignment was with the National Fire-Danger Rating System research work unit, developing the 1972 National Fire-Danger Rating System. In 1975 he transferred to the Northern Forest Fire Laboratory, Missoula, Mont., as leader of the National Fire-Danger Rating System research work unit to develop the 1978 National Fire-Danger Rating System. In 1978 he joined the Forest Residues and Energy program at the Pacific Northwest Forest and Range Experiment Station in Portland, Oreg.

ROBERT E. BURGAN received his bachelor's degree in forest engineering in 1963 and his master's degree in forest fire control in 1966 from the University of Montana. From 1963 to 1969 he served on the timber management staff of the Union and Bear-Sleds Districts, Wallowa-Whitman National Forest. From 1969 to 1975 he was a research forester on the staff of the Institute of Pacific Islands Forestry, Honolulu, Hawaii. He transferred to the National Fire-Danger Rating System research work unit at the Northern Forest Fire Laboratory, Missoula, Mont., in 1975. In 1978 he transferred to the Fire Behavior research work unit at the Northern Forest Fire Laboratory.

JACK D. COHEN received his bachelor's degree in forest science from the University of Montana in 1973 and his master's degree in bioclimatology from Colorado State University in 1976. He did environmental air quality research before joining the National Fire-Danger Rating System research work unit at the Northern Forest Fire Laboratory, Missoula, Mont., in May 1976. In 1979 he transferred to the Forest Fire Meteorology Project at the Pacific Southwest Forest and Range Experiment Station in Riverside, Calif. He has since joined the Prescribed Fire Project at Riverside.

RESEARCH SUMMARY

The National Fire-Danger Rating System (NFDRS), implemented in 1972, was revised during a 3-year project (1975 to 1978) and reissued as the 1978 NFDRS. This report describes the developmental history of the NFDRS and its technical foundation.

Detailed information is provided on modeling forest fuels and fuel moisture, and on development of the NFDRS components and indexes. The report presents equations used in the 1978 NFDRS and an extensive bibliography.

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The 1978 National Fire-Danger Rating System: Technical Documentation

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HISTORY AND BACKGROUND

Fire control conferences called by the Forest Service, U.S. Department of Agriculture, in Ogden, Utah, in 1940 and 1954 highlighted the need for a uniform fire-danger rating system that could be applied nationwide. Conference committees recommended that the system focus on the environmental factors controlling the moisture content of fuels.

In 1954, several different fire-danger rating systems were in use across the Nation. Improved communications and transportation, however, were making possible mutual assistance agreements among fire control organizations. State compacts and agreements among Federal agencies and regions brought together fire control teams from widely dispersed sections of the country. A uniform system of rating fire danger and fire behavior was therefore essential for efficient communication among all those concerned with wildland fires.

In 1958, a committee of Forest Service fire research and wildfire control personnel decided that development of a national fire-danger rating system was feasible. In June, the Washington Office Division of Fire Research organized a team headed by John Keetch, Washington Office, Aviation and Fire Management, to formulate and develop the system. Full-time work began a year later.

By 196l, the basic structure of a four-phase fire-danger rating system had been outlined, but only the first phase, fire spread, was ready for field testing. The spread phase provided two indexes to predict the relative forward spread of a fire—one for fires burning in a comparatively closed environment under a timber canopy (timber spread index), and the other for fires burning in open areas of fine fuels. A third number, the buildup index (BUI), was designed to indicate the cumulative drying of the heavier fuels. The BUI was used in the computation of the timber spread index. Following field testing in 1962 and 1963, the Forest Service issued a handbook in 1964 (FSH 5109.11) covering the spread phase of the planned development. By the next year, most fire control organizations in the United States were using at least a modified version of the spread index.

The regional adaptations that quickly followed indicated that the spread index was not uniformly applicable across the country. Furthermore, because the remaining phases—ignition, risk, and fuel energy—were not available, many fire control agencies failed to adopt the new system, preferring instead to continue using in-place fire-danger methods. The Keetch project was closed before these three phases were developed.

In 1965, a research unit at Seattle, Wash., led by Donald F. Flora, took a new look at the needs and requirements of a national system. A research forester working for Flora, James E. Hefner, surveyed fire control agencies throughout the country, analyzed their requirements, and recommended that research leading to the completion of the National Fire-Danger Rating System be resumed.

In 1968, the Forest Service established the National Fire-Danger Rating System research work unit at Fort Collins, Colo. (appendix A). Led by research meteorologist Mark J. Schroeder, the unit formulated the following goals:

1. A 1972 target date was set to complete development of the system for field use. Fire researchers agreed that a fire-danger rating system superior to any currently in use could be developed from knowledge at hand; it was not necessary to wait until all pertinent research was completed.

2. The system would be structured to enable information such as better prediction equations and improved fuel models to be readily incorporated. Such refinements would take the form of updated computer programs or new tables supplied to users; the basic format and definitions were to remain unchanged.

3. The system would be introduced as a complete, comprehensive package, not index by index.

4. The complete system would include a subjective evaluation of "risk." The development of an objective method would be deferred until the physics of fuel moisture relationships and fire behavior had been developed sufficiently to meet the needs of the system.

5. Ultimately, the system would be purely analytical, based on the physics of moisture exchange, heat transfer, and other known aspects of the problem. Although laboratory and field checks would be made and experimentation needed to establish basic relationships, the fire behavior based aspect of the system would not be based on empirical studies or statistics.

6. The system would be evaluated and updated by 1978.

In 1970, a preliminary version of the system was tested in Arizona, New Mexico, and Georgia. Eight National Forests, one Bureau of Land Management (BLM) district, two National Park Service (NPS) units, and the Georgia Forestry Commission participated (see appendix A). In 1971, an improved version was tested in the Southwest. The Forest Service, BLM, NPS, Bureau of Indian Affairs (BIA), and State agencies conducted field trials at nearly 150 locations in the continental United States and Alaska.

The 1972 National Fire-Danger Rating System (NFDRS) (fig. 1) provided three fire behavior components and three indexes for rating fire danger. It had five fuel classes (three dead, two live), nine fuel models, and three slope classes. Live fuel moisture was estimated by measuring the ratio of green material to total "fine" plant material in ten 1-foot-diameter ground samples along a 300-foot transect (Fosberg and Schroeder 1971). Separate but crude risk factors for both man-caused and lightning-caused fires were provided. These were combined with a single ignition component to provide an occurrence index (a number related to the potential fire incidence within a rating area). All of the components and indexes of the 1972 NFDRS were normalized on a scale of 0 to 100.

Forest Service Research Paper RM-84 (Deeming and others 1972, revised 1974) was the summary publication of the development effort. RM-84 was written for the field user and contained complete instructions for computation and application of the components and indexes for its nine fuel models. It was nontechnical and qualitative, but a technical development paper was prepared as an office report (Schroeder and others 1973). Much of the material here is from that report.

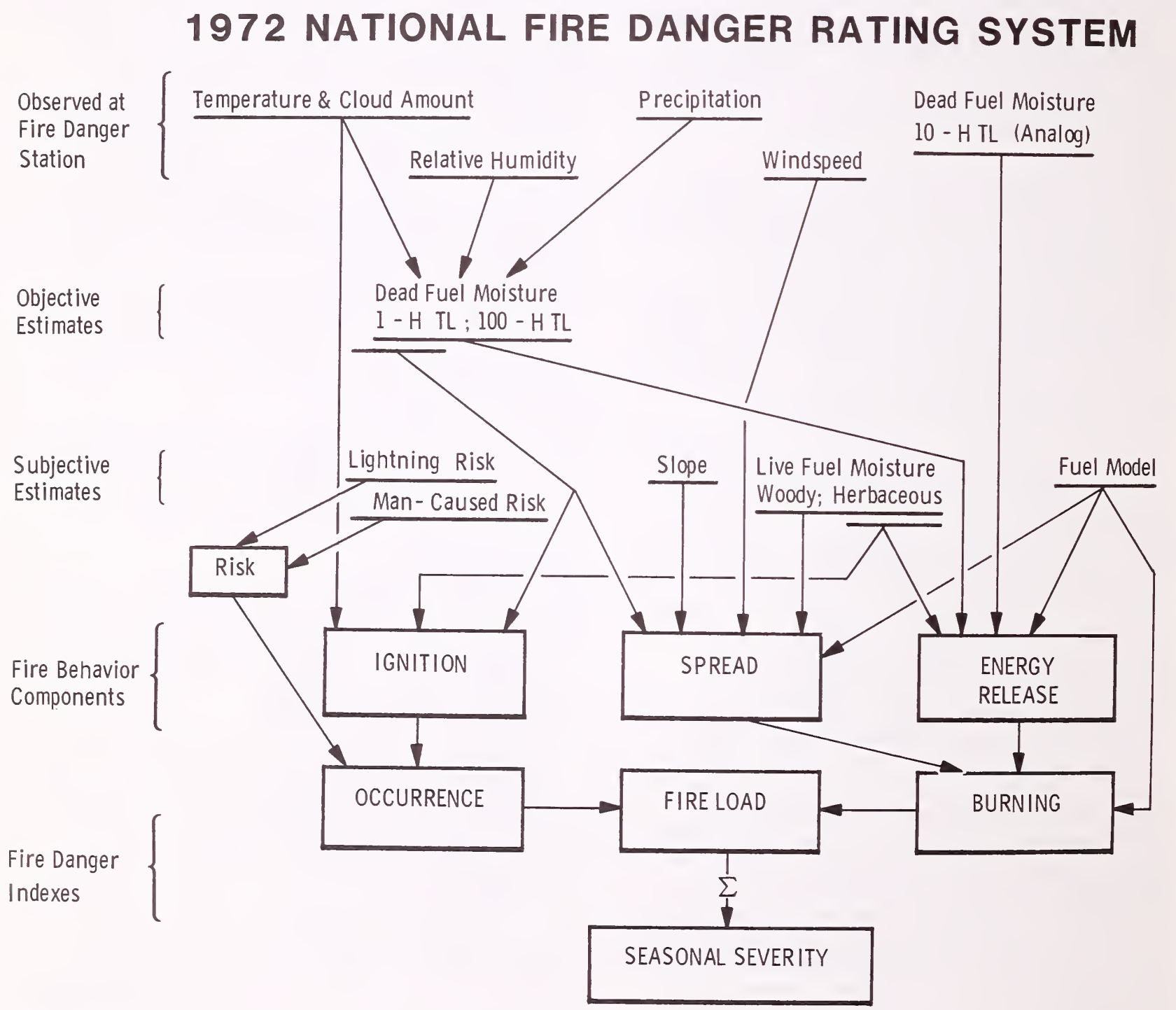

Figure 1.—Structure of the 1972 National Fire-Danger Rating System (from Deeming and others 1972, revised 1974, p. 3).

In 1973, the computer program FIRDAT (Furman and Helfman 1973) was made available at the U.S. Department of Agriculture's Fort Collins Computer Center (FCCC) to process historical fire-weather data through the NFDRS algorithms. In 1975, the National Fire-Weather Data Library (NFWDL) for archival and retrieval of fire-weather data was developed and installed at FCCC (Furman and Brink 1975). FIRDAT and the NFWDL provided a systematic means of developing fire-weather and fire-danger climatologies, which are critically important for fire management planning.

The same year, after 4 years of development and testing, the entire fire-danger rating process was computerized in the AFFIRMS processor (Helfman and others 1975, revised 1980). AFFIRMS, an interactive time-share program, computes fire-danger ratings from daily fire-weather observations and forecasts and creates fire-weather data tapes that are incorporated into the NFWDL at FCCC.

By the summer of 1976, data from more than 800 fire-weather stations across the United States were being processed through AFFIRMS, and the system indexes and components were being calculated manually each day for some 400 stations. By the spring of 1977, all Federal agencies and 35 State agencies charged with forest and rangeland fire protection responsibilities were using the 1972 version of the National Fire-Danger Rating System.

Responsibility for the 1978 NFDRS update was given to John E. Deeming who had joined the NFDRS project at Fort Collins, Colo., in 1970. The project was relocated to the Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory, Missoula, Mont., during the summer of 1975. Deeming was joined that summer by Robert E. Burgan and the following spring by Jack D. Cohen, both research foresters. The 1978 update reflects changes made possible by feedback from 1972 system users and advances in fire science and fuels technology.

The 1978 National Fire-Danger Rating System update addressed several major problems identified in the 1972 system:

Response to drought.—The 1978 update has improved response to short-term drought, with the addition of a 1,000-hour timelag dead fuel class, and the inclusion of live fuels in all but the slash fuel models. Live fuel moisture models emulate plant moisture response to phenological cycles, replacing the fuel moisture transects used in the 1972 NFDRS.

Seasonal sensitivity.—Calculation of fuel moisture for the 100-hour and 1,000-hour timelag fuels was altered to account for a day's drying power as affected by day length. Day length is calculated from the date and a fire-weather station's latitude.

Component sensitivity.—The 1972 system had its components and indexes normalized to a 0 to 100 scale, which often caused moderate fire climates to never see a rating greater than 10. The spread and energy release components, and the burning index now have open-ended scales that yield a threefold to fivefold increase in sensitivity.

Occurrence indexes.—The 1978 NFDRS has separate occurrence indexes for man-caused and lightning-caused fires (the 1972 system had only one occurrence index for both types of fires). The occurrence index models in the 1978 update reflect major improvements over the simplistic model used in the 1972 system.

Ignition component.—The 1978 NFDRS ignition component is a function of the probability of ignition and spread component. The 1972 system's ignition component was simply the probability of ignition.

More fuel models.—The 1978 NFDRS offers 20 fuel models to describe a fuel situation; the 1972 system had 9.

Better slope definition.—The 1978 NFDRS has five slope classes to describe an area's topography; the 1972 system had three. Two slope classes were added to cover steep terrain (greater than 50 percent slope).

Live fuel moisture models.—The 1978 NFDRS introduced models for computing the fuel moisture of live herbaceous and shrub fuels. The model also causes herbaceous material, when cured, to be transferred to the 1-hour dead fuel loading class to better emulate actual fire danger prior to spring green-up and after autumn curing.

A summary publication (Deeming and others 1977) describes the 1978 NFDRS and, for NFDRS users not on the AFFIRMS network, there is a manual version of the 1978 system (Burgan and others 1977). The 1978 National Fire-Danger Rating System is now being used by most Federal, State, and private agencies charged with wildland fire protection. The 1978 changes have been included in new releases of FIRDAT and AFFIRMS (Main and others 1982; Helfman and others 1975, revised 1980).

PHILOSOPHY

The development and application of both the 1972 and 1978 NFDRS's are grounded in six major principles:

1. The system would consider only the "initiating fire." This is defined as a fire that is not behaving erratically; it is spreading without spotting through fuels that are continuous with the ground (no crowning). The "state of the art" does not yet extend to fires that exhibit erratic behavior other than to show that extreme behavior is correlated with increasing fire danger.

2. The system would provide a measure of that portion of the potential job of containment that is attributable to fire behavior. The concept of containment as opposed to extinguishment is essential because it limits the fire behavior prediction to the head of the fire. Those portions of the containment job dealing with accessibility, soil condition, and resistance to line construction must still be evaluated by other means.

3. The length of the flames at the head of the fire was assumed to be directly related to the contribution of fire behavior to the containment job.

4. The system would attempt to evaluate the "worst" conditions on a rating area by using meteorological measurements taken (a) when fire danger is normally the highest (usually in the early afternoon), (b) at sites in the open, and (c) where possible, at sites on drier (southerly

or westerly) exposures. This means that extrapolation of fire-danger values to areas other than those immediately in the vicinity of the fire-danger station would involve scaling down, not up.

5. The system would provide ratings that would be physically interpretable in terms of fire occurrence and behavior. These evaluations could then be used alone or in combinations, giving the user the flexibility needed to deal with the entire spectrum of fire control planning problems.

6. Ratings would be relative, not absolute. The ratings would be linearly related to the particular aspect of fire danger being evaluated. This means that when a component or index doubles, a doubling of the rated activity relative to what has previously been observed should be anticipated. Because of the many variables in the computations, the low spatial and temporal resolution of fuels and weather data, and incomplete understanding of some relationships, fire danger can only be broadly defined within a rating area.

STRUCTURE

The 1978 NFDRS (fig. 2) provides four indexes to facilitate the planning of fire control activities: the man-caused fire occurrence index (MCOI); the lightning-caused fire occurrence index (LOI); the burning index (BI); and the fire load index (FLI).

The MCOI is derived from man-caused risk (R_{MC}), an assessment of man-caused fire sources in the rating area, and the ignition component (IC), the likelihood that a firebrand will cause a reportable fire.

The lightning-caused fire occurrence index (LOI), similar in concept to the MCOI, is derived from the ignition component (IC) and lightning risk (R_L), an indicator of thunderstorm and lightning activity. After being scaled to an area's experience, both the MCOI and LOI can be used to predict, on the average, the total expected number of reportable fires that will occur on a rating area.

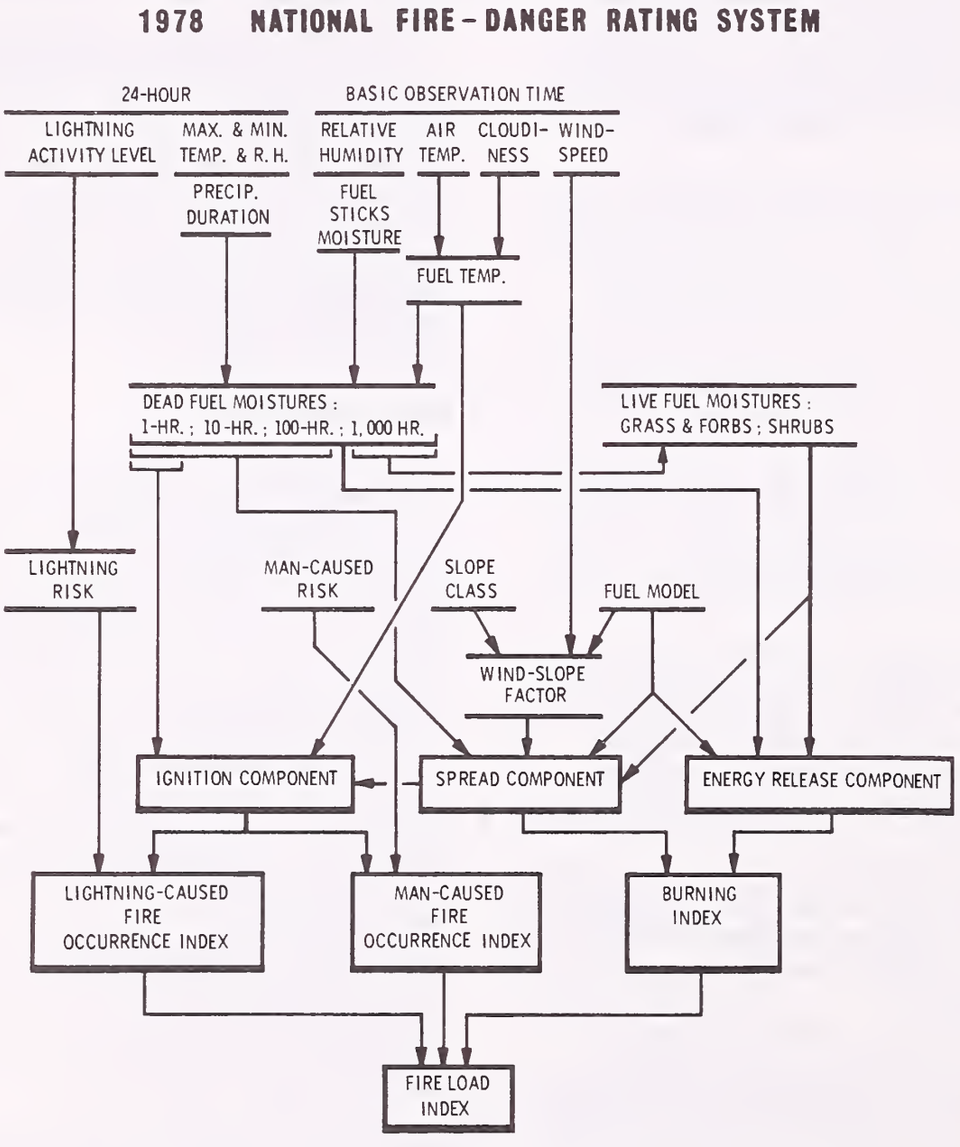

Figure 2.—Structure of the 1978 National Fire-Danger Rating System (from Deeming and others 1977, p. 6).

The burning index is derived from the spread component (SC), a relative index of rate of fire spread, and the energy release component (ERC), a relative index of the amount of heat released per unit area in the flaming zone of an initiating fire. Considered together, they indicate the difficulty of containment. The combined index, BI, is linearly related to the length of flames at the head of the fire.

The difficulty of containing a single fire (the BI) and the expected number of fires projected by the MCOI and LOI combine to produce the fire load index (FLI), a measurement of the total fire containment job. The FLI is the NFDRS cumulative index, integrating risk, ignition probability, and fire behavior potential.

The risk ratings (R_{MC} and R_L), man-caused fire occurrence index (MCOI), lightning-caused fire occurrence index (LOI), ignition component (IC), and fire load index (FLI) are expressed on a scale of 0 to 100. The scales of the spread component (SC), energy release component (ERC), and burning index (BI), are open ended.

Eleven elements of a fire-weather observation drive the various models that make up the National Fire-Danger Rating System. Observation time (early to midafternoon) elements are:

1. Temperature, °F,
2. Relative humidity, percent,
3. State of the weather,
4. Ten-minute average 20-ft windspeed (mi/h), and
5. Fuel stick moisture, percent.

Elements for the 24-hour period ending at the observation time are:

6. Duration of precipitation, hours,
7. Amount of precipitation, inches,
8. Maximum 24-hour temperature, °F,
9. Minimum 24-hour temperature, °F,
10. Maximum 24-hour relative humidity, percent, and
11. Minimum 24-hour relative humidity, percent.

NOTE: AFFIRMS will also accept metric environmental inputs.

Dead fuels are stratified by moisture response timelag classes (1, 10, 100, and 1,000 hours); live fuels by type of vegetation (grass-forbs or woody shrubs). Fuel classifications are discussed in the section titled "Classification of Fuel Components," under "Forest Fuels"; fuel moisture calculations are covered in sections titled "Dead Fuel Moisture Models" and "Live Fuel Moisture Models." Precipitation duration affects fuel moisture more significantly than does precipitation amount. The 24-hour precipitation amount is recorded because it is a standard climatological element.

The traditional fuel moisture sticks are used as an analog of the 10-hour timelag fuel class. A set of sticks is an array of three 1/2- by 18-inch ponderosa pine dowels. The ovendry weight of fuel sticks decreases with extended weathering, so a correction for age is applied.

Fuel particle and fuel bed property values are quantified in the system's 20 stylized fuel models. Fuel models consist of fuels information required for input to the system's SC and ERC models. A fuel model contains fuel characteristic values typical of fuel descriptions for a general cover type.

Wind, slope, fuel moistures, and fuel descriptors (via fuel models) are required to compute the SC and ERC using a modification of the Rothermel (1972) fire spread model (see section titled "Fire Behavior Model"). The burning index computations are based on Byram's flame length model (Byram 1959). The specifics of the 1978 NFDRS indexes and components SC, ERC, BI, IC, MCOI, LOI, and FLI are discussed in sections titled "Fire Behavior Components," "Ignition Component, Risk, and Occurrence Indexes," and "The Fire Load Index."

FOREST FUELS

The delineation of wildland fuel characteristics for fire behavior modeling and resultant fire-danger rating is based on quantitative descriptions of fuel particle and fuel bed properties. The important fuel particle properties are size, density, chemical composition, and shape (a cylindrical shape is assumed). Important fuel bed characteristics are fuel amounts (dry weight load by size class, lb/ft^2) and fuel bed depth. (The fuel bed is assumed to be uniform and continuous, and the various fuel classes uniformly distributed throughout the fuel bed.) Stylized fuel models are discussed in the section titled "Fuel Models."

Classification of Fuel Components

DEAD FUELS

Dead fuels are fuels in which the moisture content is exclusively controlled by environmental conditions—temperature, radiation, relative humidity, and precipitation.

The relationships among environmental conditions and dead fuel moisture in the 1978 NFDRS draw heavily upon definitions and theory proposed by Byram (1963) and expanded on by Fosberg (1970). Byram demonstrated that the moisture content of dead fuels drying under constant conditions follows an exponential decay curve. He defined the timelag interval, τ, as the time required for fuels to lose approximately two-thirds of their initial moisture content (the actual amount is $1-1/e$, where e is the base of natural logarithms).

Byram defined the relative moisture content, μ, as:

$$\mu = \mu_o \cdot \exp(-\tau T) \quad (\%) \quad (1)$$

where

T is the period of environmental stress (h),

τ is the fuel particle timelag (h), and

μ_o is the initial moisture content of the fuel particle (%).

The relative moisture content (%) may also be defined:

$$\mu = (EMC - \bar{\mu})/(\mu_o - \bar{\mu}) \quad (2)$$

where

$\bar{\mu}$ is the mean moisture content (%) over the time period,

EMC is the equilibrium moisture content (%), and

μ_o is the initial moisture content (%) at the onset of the stress period.

Equilibrium moisture content (EMC) is the moisture content dead fuels would obtain if left in a steady-state environment long enough to obtain equilibrium (no net moisture exchange). It is computed using the fuel-atmosphere interface dry bulb temperature and relative

humidity. Computation of EMC values is discussed further in the section titled "The 1-Hour Timelag Fuel Moisture Models," and appendix C.

Fosberg (1970) then introduced similarity theory expressed by a Fourier number (F_0). Using both experimental and theoretical methods, Fosberg and others (1970) showed the Fourier number to be a universal constant for fuel moisture. For cylindrical fuels, the Fourier number is

$$F_o = (\tau\nu)/r^2 \quad (3)$$

and for the general case

$$F_o = (\tau\nu\sigma^2)/(4\chi_s^2) \quad (4)$$

where

τ is the particle's moisture timelag (h),

ν is the characteristic moisture diffusivity of the fuel particle (cm^2/min),

r is the fuel particle radius (cm),

σ is the particle's surface area-to-volume ratio (see section titled "Fuel Particle Properties"), and

χ_s is a fuel particle shape factor (not used in the NFDRS).

In both cases, $F_o = 0.18$.

Experimentally determined, diffusivity inherently contains information on the species, and thus automatically accounts for the presence of waxes and resins that hinder fuel moisture transport. Some typical values of ν are given in table 1 for selected species.

Fosberg (1971b) then used the Fourier number to solve for a characteristic timelag similarity coefficient (ζ), and defined the change of moisture content for transient surface conditions as:

$$\delta\mu/\Delta\mu = 1 - \zeta \cdot e^{(-T/\tau)} \quad (5)$$

where

$\delta\mu$ is the actual moisture content change (%) in the stress period (T, h),

$\Delta\mu$ is the potential moisture content change (%) in the stress period (T),

ζ is the similarity coefficient (dimensionless),

e is the base of the natural logrithms, and

τ is the fuel particle timelag (h).

$\Delta\mu$ may be estimated from the difference in the EMC at the beginning and end of the stress period as calculated from the initial and ending fuel-atmosphere temperatures and relative humidities. This equation provides the basis for theoretical calculation of dead fuel moisture.

The range of moisture contents over different time intervals is characteristic of fuel particle size. Figure 3 illustrates a normal diurnal cycle in which the moisture content of fine fuels vary widely. Intermediate-sized fuels vary within a narrower range, and large fuels within a very limited range (Gisborne 1928; Brackebusch 1975).

Using equation 5, Fosberg (1971a) simulated the magnitude of the range of moisture responses of fuels with different timelags to weather cycles of 1-day (diurnal), 4-day (synoptic), 30-day (planetary), and 1-year (annual). He used climatological data from 10 locations to represent the diurnal variation of boundary value moisture content and data from 2 locations to represent the annual variations of boundary moisture content.

Table 1.—Typical diffusivity values for selected forest fuels (from unpublished 1972 NFDRS documentation)

Fuel type	Diffusivity
	cm^2/s
Ponderosa pine dowel (*Pinus ponderosa*)	
0.159 cm radius	8.32×10^{-7}
0.318 cm radius	8.32×10^{-7}
0.635 cm radius	8.32×10^{-7}
1.0 cm radius	8.32×10^{-7}
1.27 cm radius	8.32×10^{-7}
2.54 cm radius	8.32×10^{-7}
5.08 cm radius	8.32×10^{-7}
Douglas-fir dowel (*Pseudotsuga menziesii*)	
1.0 cm radius	8.30×10^{-7}
Lodgepole pine dowel (*Pinus contorta*)	
1.0 cm radius	8.42×10^{-7}
Alaska cedar dowel (*Chamaecyparis nootkatensis*)	
1.0 cm radius	5.94×10^{-7}
Eastern white pine dowel (*Pinus strobus*)	
1.0 cm radius	10.3×10^{-7}
Ponderosa pine needles (*Pinus ponderosa*)	2.0×10^{-8}
Western white pine needles (*Pinus monticola*)	1.18×10^{-8}
Eucalyptus leaves (*Eucalyptus obliqua*)	4.77×10^{-8}
Quaking aspen leaves (*Populus tremuloides*)	—
Cheatgrass (*Bromus tectorum*)	
Leaves	—
Stalks	—
Plant	2.58×10^{-7}
Fescue (*Festuca idahoensis*)	
Leaves	—
Stalks	—
Plants	—

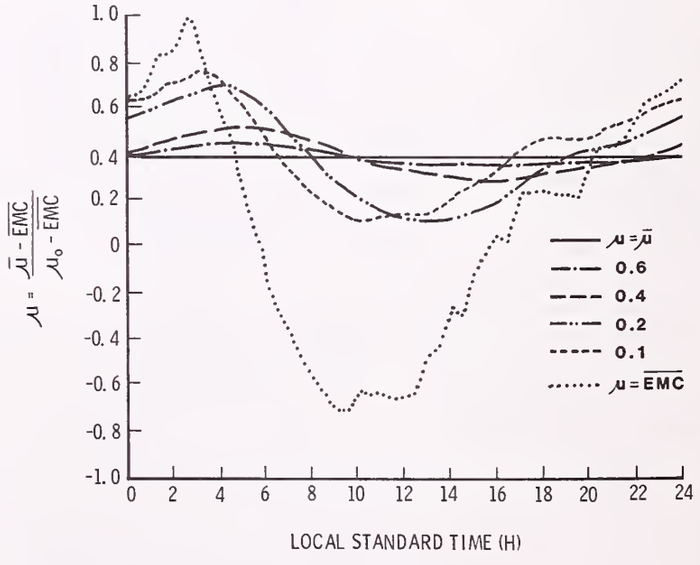

Figure 3.—Diurnal variations of relative moisture content (m) for fuels of increasing radii (adapted from Fosberg 1971a, p. 68).

Figure 4 shows the relative ranges of moisture content ($\Delta\mu$) plotted over timelag (τ) for the four timelag periods.

The range of moisture content in each case period is

$$\Delta\mu = (\mu_{max} - \mu_{min}) \quad (6)$$

where

μ_{max} is the period maximum moisture content (%), and
μ_{min} is the period minimum moisture content (%).

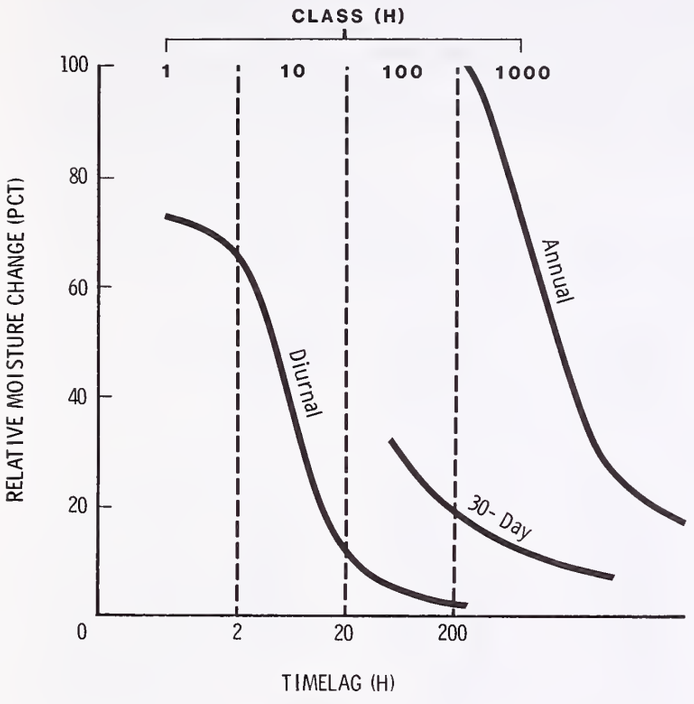

Figure 4.—Moisture recovery curves for fuel particles of increasing radii (adapted from unpublished 1972 NFDRS documentation).

The $\Delta\mu$'s for a given time period characterize fuel particles of a given timelag. As τ increases, $\Delta\mu$ decreases if the period is constant. As time periods increase, fuel particles with a constant τ exhibit a larger $\Delta\mu$.

This relationship provided a basis for dead fuels classification (Lancaster 1970). The recovery curves, all having a reverse S-shape, are characterized by three straight-line segments. For the diurnal cycle, fuels with a timelag less than 2 hours show a high recovery; those with timelags greater than 20 hours show a low recovery. Fuels with timelags less than 200 hours show an intermediate recovery range for the 30-day cycle and a high recovery range for the annual cycle.

Based upon these differences, four groupings of timelags were delineated: fuels with timelags up to 2 hours; from 2 to 20 hours; from 20 to 200 hours; and more than 200 hours. Each group responds uniquely to successively longer cycles. The approximate midpoints of these timelag ranges are used as the basis for a classification scheme: 1-hour, 10-hour, 100-hour, and 1,000-hour timelag fuels.

Exposed mosses, lichens, and cured grasses and herbs have timelags of 1 hour or less. The uppermost layer of weathered conifer needles on a forest floor typically respond to environmental stress within 2 hours, as do dead twigs of woody plants up to ¼-inch diameter. Fresh conifer needles exhibit timelags ranging from 1 to 10 hours, but approach 1 hour as waxes and resins are leached away (Van Wagner 1969; Anderson and others 1978).

The 10-hour class includes dead twigs and branches from one-fourth inch to 1 inch in diameter. Dead branchwood in the 1- to 3-inch diameter class falls into the 100-hour timelag group, and dead logs and branchwood from 3 to 8 inches constitute the 1,000-hour timelag class. The dead fuel moisture models for each size class of dead fuel are presented in the section titled "Dead Fuel Moisture Models," with subsections on the 1-hour, 10-hour, 100-hour, and 1,000-hour timelag fuel moisture models.

LIVE FUELS

In living fuels moisture content is controlled by the physiological processes of the plant. Changes in moisture of the two classes of live fuels considered by the 1978 NFDRS are both seasonal and short term. These classes are herbaceous plants (grasses and forbs) and woody shrubs. Dynamic live fuel moisture models have been developed to simulate the greening and curing process of these fuels through a growing season and also short-term moisture content fluctuations due to extreme environmental conditions. The live fuel moisture models are discussed in the section titled "Live Fuel Moisture Model."

Herbaceous Plants

Plants that do not develop persistent woody tissues such as grasses, forbs, and ferns make up the NFDRS herbaceous fuel class. The herbaceous class is further subdivided into annual and perennial types. When the fuel moisture falls below 30 percent, these plants are considered cured and the moisture content defaults to that of the 1-hour timelag fuels. The herbaceous fuel moisture model is presented in the section titled "Herbaceous Fuel Moisture."

Woody Shrubs

The second category of live fuel in the 1978 NFDRS is the perennial woody shrub. These fuels are considered dormant when the moisture content falls to 50 percent. Above this value these plants are allowed a maximum moisture content of 250 percent during the growing season. The woody shrub fuel moisture model does not allow the estimated shrub moisture content to fall so low that the shrubs would have to be considered dead. But at the low end of their moisture range they are considered dormant. The woody fuel moisture model is presented in the section titled "Woody Fuel Moisture Model."

Fuel Particle Properties

The physical and chemical fuel particle properties described in this section were originally defined by Rothermel (1972). These properties and fuel moisture response to environmental stress (via fuel size) are fundamental to rating fire danger. Physical characteristics such as fuel particle size and shape affect the ease of ignition and rate of moisture exchange with the environment. The energy potentially available through combustion is a chemical property.

PHYSICAL PROPERTIES

Fuel Particle Surface Area-to-Volume Ratio (σ)

The gain and loss of heat and moisture and the evolution of combustible gases occur through the surface of a fuel particle and occur at rates directly related to the amount of surface area per unit volume of the particle. Thus the surface area-to-volume ratio (σ) of a fuel particle is a very important fuel particle property. Fuel particles with large σ's will ignite more readily than those with relatively small σ's. For a cylinder, the surface area-to-volume ratio is inversely related to the radius.

The surface area (neglecting end area) of a cylinder, A, is

$$A = 2\pi rL \quad (ft^2) \tag{7}$$

and its volume

$$V = \pi r^2 L \quad (ft^3) \tag{8}$$

where r is the radius and L is the length. The surface area-to-volume ratio for cylindrical fuels is

$$\sigma = A/V = (2\pi rL)/(\pi Lr^2) = 2/r \quad (1/ft). \tag{9}$$

Fuel Particle Density (ϱ_p)

The next important fuel particle property is the density, ϱ_p. This is needed to determine the packing ratio, β (see section titled "Fuel Compactness"), of a fuel bed. A ϱ_p value of 32 lb/ft^3 is used for both live and dead fuels in all of the fuel models.

Table 2 contains typical values of σ and ϱ_p for selected fuel particles.

Table 2.—Typical fuel particle properties of selected forest fuels (from unpublished 1972 NFDRS documentation)

Fuel Type	Shape Factor (ψ)	Surface area vol ratio (σ, cm^{-1})	Cross sectional area (A, cm^2)	Particle density (ϱ, g/cm^3)	Timelag (τ, h)
Ponderosa pine dowel					
Pinus ponderosa					
0.159 cm radius	1	12.6	0.079	0.418	1.5
.318 cm radius	1	6.3	.317	.418	6.1
.635 cm radius	1	3.15	1.27	.418	24.0
1.0 cm radius	1	2.0	3.14	.418	59.0
1.27 cm radius	1	1.57	5.07	.418	97.0
2.54 cm radius	1	.787	20.3	.418	388.0
5.08 cm radius	1	.394	81.1	.418	1,551.0
Douglas-fir dowel					
Pseudotsuga menziesii					
1.0 cm radius	1	2.0	3.14	.508	59.0
Lodgepole pine dowel					
Pinus contorta					
1.0 cm radius	1	2.0	3.14	.432	59.0
Alaska cedar dowel					
Chamaecyparis nootkatensis					
1.0 cm radius	1	2.0	3.14	.458	82.0
Eastern white pine dowel					
Pinus strobus					
1.0 cm radius	1	2.0	3.14	.362	47.8
Ponderosa pine needles					
Pinus ponderosa	1.3	57.6	6.5×10^{-4}	—	3.91
Western white pine needles					
Pinus monticola	1.3	90.5	2.6×10^{-4}	—	2.7
Eucalyptus leaves					
Eucalyptus obliqua	1.43	61.8	6.8×10^{-4}	—	1.57
Quaking aspen leaves					
Populus tremuloides	1.07	139.8	7.5×10^{-5}	—	—
Cheatgrass					
Bromus tectorum					
Leaves	1.9	189.0	1.3×10^{-4}	—	—
Stalks	—	75.8	—	—	—
Plant	—	145.0	—	—	.07
Fescue					
Festuca idahoensis					
Leaves	2.2	190.0	1.7×10^{-4}	—	—
Stalks	—	68.6	—	—	—
Plant	—	182.0	—	—	—

CHEMICAL PROPERTIES

Fuel particles have three chemical properties that affect combustion and hence must be considered by fire-danger rating: heat content, total mineral content, and effective mineral content.

Heat Content (H)

The energy available per unit mass of fuel through combustion is called the heat content. In woody fuels, on a dry weight basis, it is relatively consistent from one plant species to another. Heat content may also be referred to as the heat of combustion. In the NFDRS, this value ranges from 8,000 Btu/lb to 9,500 Btu/lb and varies by fuel model. Table 3 summarizes some typical values for western fuels.

Total Mineral Content (S_t)

Total mineral content (S_t) is the fraction of a fuel mass composed of inorganic minerals. The inorganic mineral content reduces the combustible fuel mass because only the organic portion of a fuel supports combustion. The total mineral content may also be referred to as total ash content. A value of 5.55 percent is used for both dead and live fuels in all NFDRS fuel models.

Effective Mineral Content (S_e)

The effective (active) mineral content (S_e) affects fire behavior by interfering with the chemical processes of combustion. The presence of certain mineral salts alters the pyrolysis process and promotes the formation of char and tar at the expense of more flammable volatiles. Philpot (1968, 1970) showed that the rate of thermal degradation and the amount of volatiles produced are reduced as the silica-free ash content increases. Table 4 summarizes the total ash and silica-free ash content for selected species. A value of 1 percent is used for both dead and live fuels in the NFDRS fuel models.

Table 3.—Average heat content (heat of combustion) of selected forest fuels (from Kelsey and others 1979)

Species	Wood	Bark	Twigs	Foliage
			Btu/lb	
Western redcedar	9,700	8,669	8,708	9,630
Grand fir	8,300	9,641	8,894	9,497
Western larch	8,620	9,162	9,247	8,703
Western white pine	8,620	9,355	9,464	9,040
Engelmann spruce	8,100	9,616	9,076	8,806
Lodgepole pine	8,600	9,605	9,371	9,365
Western hemlock	8,500	9,943	8,924	9,491
Douglas-fir	9,200	10,845	9,113	9,265
Ponderosa pine	9,100	9,452	10,026	9,527
Average	8,721	9,461	9,253	9,315
Sample size	35	35	43	38

Table 4.—Mineral content of selected plant materials (adapted from Philpot 1970)

Species	Part	Mineral content	
		Total ash	Silica-free-ash
		Percent dry weight	
Cellulose[1]		0.01	0.01
Douglas-fir (*Pseudotsuga menziesii*)	Wood	.11	.11
Birch (*Botula* sp.)	Wood	.18	.18
Ponderosa pine (*Pinus ponderosa*)	Wood	.22	.22
Poplar (*Populus* sp.)	Wood	.36	.36
Cheatgrass (*Bromus tectorum*)	Leaves	5.27	1.04
Medusahead grass (*Elymus caput-medusae*)	Leaves	16.02	1.17
Ponderosa pine (*Pinus ponderosa*)	Needles	3.87	1.55
Chamise (*Adenostoma fasciculatum*)	Stems	2.19	1.75
White pine (*Pinus monticola*)	Needles	3.34	2.54
Chamise (*Adenostoma fasciculatum*)	Leaves	3.63	3.33
Aspen (*Populus tremuloides*)	Leaves	5.24	5.24
Guava (*Psidium guajava*)	Green leaves	6.08	5.58
Guava (*Psidium guajava*)	Dead leaves	6.24	5.74
Guava (*Psidium guajava*)	Leaves[2]	7.79	7.29
Saltbush (*Atriplex canescens*)	Leaves	12.89	12.29
Salt tree (*Tamarix aphylla*)	Leaves	16.59	14.53
Saltbush (*Atriplex polycarpa*)	Leaves	15.39	14.83
Saltbush (*A. lentiformis v. brewerii*)	Leaves	19.26	18.63
Saltbush (*A. nuttalli v. gardnerii*)	Leaves	26.78	23.57
Saltbush (*A. gardnerii*)	Leaves	27.07	25.27

[1]Analytical fiber pulp. Carl Schleicher and Schuel Co.
[2]Treated with herbicide (2-4-D and 2-4-5-T).

Fuel Bed Properties

Five properties of fuel beds affect combustion and fire behavior:

1. Amount or loading of fuels,
2. Compactness of fuels,
3. Continuity of fuels,
4. Uniformity of fuels, and
5. Fuel element arrangement and distribution.

Only amount and compactness, however, are allowed to vary. In this and other applications of the Rothermel (1972) fire spread model, the fuel bed is assumed to be continuous and uniform, and the elements of the different fuel classes are assumed to be thoroughly "mixed" and uniformly distributed throughout the length, width, and depth of the bed.

FUEL LOADS BY SIZE CLASS

Fuel loading expresses the mass of fuel per unit area in a fuel bed. Combined with the heat content, H (Btu/lb), the net fuel load is a factor in the amount of heat available per unit area of the fuel bed (Btu/lb $\times$ lb/ft^2 = Btu/ft^2). The net fuel load (W_n) is the total fuel load (W_o) less the mass represented by the total mineral content (S_t) of the fuel particle. In combination with fuel bed depth (δ), it determines the fuel bed bulk density, ϱ_b:

$$\varrho_b = W_o/\delta \quad (\text{lb/ft}^3) \qquad (10)$$

where

W_o is the total dry fuel bed load (lb/ft^2), and
δ is the fuel bed depth (ft).

FUEL COMPACTNESS (β,ϕ)

The compactness of a fuel bed is expressed as fuel bed porosity(ϕ), or packing ratio (β). Packing ratio is the ratio of the density of the fuel bed (ϱ_b) to the fuel particle density (ϱ_p):

$$\beta = \varrho_b/\varrho_p \quad (\text{dimensionless}) \qquad (11)$$

and the porosity is the dimensionless ratio of the fuel bed void volume to the total fuel bed volume:

$$\phi = V_v/V_b = (V_b - V_f)/V_b \quad (\text{dimensionless}) \qquad (12)$$

where

V_v is the bed void volume (empty space, ft^3),
V_f is the bed fuel volume (ft^3), and
V_b is the total bed volume (ft^3).

ϕ, β, and ϱ_b are interrelated as follows:

$$\phi = (\varrho_p - \varrho_b)/\varrho_p, \qquad (13)$$

$$\varrho = 1 - \beta. \qquad (14)$$

MOISTURE OF EXTINCTION (m_x)

The fuel moisture content at which a fire will not propagate in a fuel bed is the moisture of extinction. In the 1972 NFDRS, 30 percent, which is close to the fiber saturation value for woody material, was used as the moisture of extinction. But Brown (1972) and Blackmarr (1972) found that moisture of extinction values vary with fuel bed compactness, fuel particle size, windspeed, and slope. They found extinction moisture contents ranging from 12 percent in grass to 40 percent in conifer litter. Current research at the Northern Forest Fire Laboratory should provide better guidelines for future use.

Lacking better information, the NFDRS makes several assumptions; the first is that live and dead fuels have different moistures of extinction, and that a specific fuel complex has a constant moisture of extinction for its dead fuel components.

Dead Fuel Moisture of Extinction (m_{xd})

The dead fuel moisture of extinction is a fuel-model-dependent value, with values ranging from 15 percent in the grass and brush models to 30 percent for the southern rough, pine, and pocosin models.

Live Fuel Moisture of Extinction (m_{xl})

A more extensive method is used for live fuels because their moisture contents are typically much greater than fiber saturation. Fosberg and Schroeder (1971) assumed that the heat produced by a burning mass of fuel and transferred to an equal mass of unburned fuel having a 30 percent moisture content is just sufficient to raise the temperature of the unburned fuel to ignition. As the moisture content of the unburned fuel nears zero percent, only a very small amount of heat is needed to raise the fuel temperature to ignition. When a linear relationship is assumed, these two points define the relationship between moisture content and effective heat energy (line A in fig. 5).

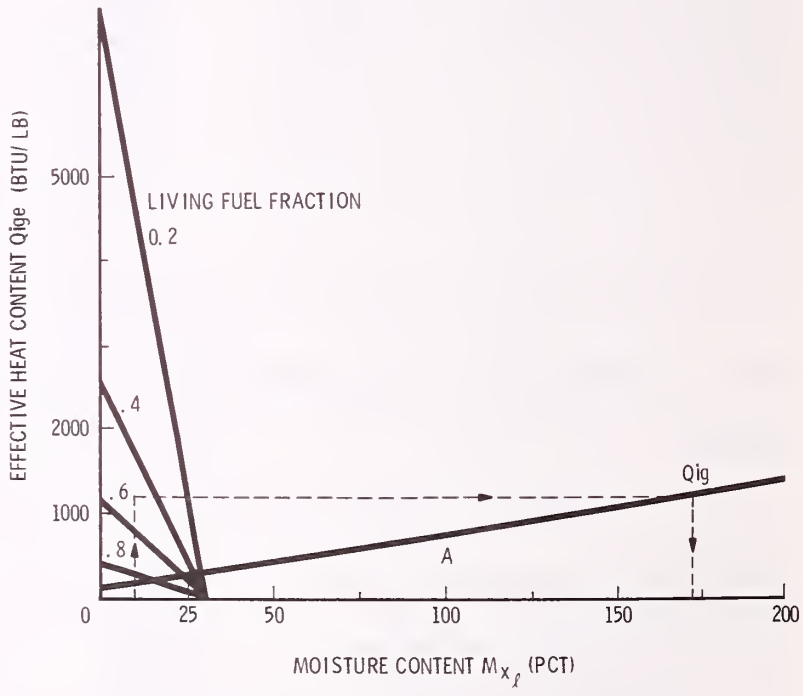

Figure 5.—Relationship between live moisture content and effective heat energy (adapted from Fosberg and Schroeder 1971, p. 3).

If the burning fuel is considered dead, and the unburned fuel live, the extinction moisture content for various proportions of live and dead fuels can be estimated over the range of dead fuel moisture content from zero to 30 percent.

Fosberg and Schroeder (1971) used the heat of preignition (Q_{ig}) per unit mass (a function of moisture content) from the Rothermel (1972) rate of spread model to estimate the effective heat energy.

In metric units:

$$Q_{ig} = 140 + 620m_f \quad (15)$$

where m_f is the 1-hour fuel moisture (fraction).

Effective heat transfer (Q_{ige}) is a function of fractional living fuel and dead fuel moisture:

$$Q_{ige} = 1{,}800((1 - \alpha)/\alpha)(1 - \frac{10}{3} m_f) \quad (16)$$

where

α is the fraction of living fuel, and

m_f is the 1-hour dead fuel moisture (fraction).

At the moisture of extinction (assumed $m_x = 0.3$), $Q_{ig} = Q_{ige}$:

$$140 + 620m_{xl} = 1{,}800((1 - \alpha)/\alpha)(1 - \frac{10}{3} m_f) \quad (17)$$

where m_{xl} is the extinction moisture content (fractional) of the unburned fuel. Solving for m_{xl}:

$$m_{xl} = 2.9((1 - \alpha)/\alpha)(1 - \frac{10}{3} m_f) - 0.226 \quad (18)$$

gives the m_{xl} as a fraction. It is multiplied by 100 to convert to percent.

$$m_{xl} = 290((1 - \alpha)/\alpha)(1 - \frac{10}{3} m_f) - 22.6. \quad (19)$$

This expression was modified by Albini (1976b) using the effective heating number concept introduced by Frandsen (1973). The heating number, a fuel load weighting factor of the form $e(-k/\sigma)$ is used to compute a dead-to-live loading ratio (W), and a weighted "fine" dead fuel moisture, m_{fw}. Albini's final expression is

$$m_{xl} = 290W(1 - m_{fw}/m_{xd}) - 22.6 \quad (20)$$

where

m_{xl} is limited to the minimum m_{xd} value,

m_{xd} is the dead fuel moisture of extinction for the fuel bed,

$$W = \frac{\sum_{j=1}^{3} \overline{W}_{n1j} \exp(-138/\overline{\sigma}_{1j})}{\sum_{j=1}^{2} \overline{W}_{n2j} \exp(-500/\overline{\sigma}_{2j})} \quad (21)$$

and

$$m_{fw} = \frac{\sum_{j=1}^{3} m_{lj} W_{lj} \exp(-138/\overline{\sigma}_{1j})}{\sum_{j=1}^{2} W_{n1j} \exp(-138/\overline{\sigma}_{1j})} \quad (22)$$

and where

W_{n1j} is the net dead fuel load (j indicates 1-hour, 10-hour, or 100-hour timelag class),

W_{n2j} is the net live fuel load (j indicates woody or herbaceous),

m_{1j} is the dead fuel moisture content (fraction),

σ_{ij} is the surface area-to-volume ratio,

$\exp(-138/\sigma_{1j})$ is the dead fuel effective heating number, and

$\exp(-500/\sigma_{2j})$ is the live fuel effective heating number.

This expression, in conjunction with the live fuel moisture model, is used for computing moisture damping coefficients for herbaceous and woody fuels in the fire model.

FUEL MODELS

The previous section described the classification of fuel particles and defined eight fuel particle and bed characteristics that are important in fire behavior modeling and resultant fire-danger rating. These eight parameters:

H.....heat content, Btu/lb
ϱ_p....fuel particle density, lb/ft^3
S_t.....total mineral content, %
S_e....effective mineral content, %
w_o....total dry fuel bed load, lb/ft^2
δ.....fuel bed depth, ft
σ,.....surface area-to-volume ratio, ft^2/ft^3, and
m_x...moisture of extinction, %

are the parameters that are quantified in the NFDRS fuel models. A fuel model is a set of the fuel particle and fuel bed descriptors required as inputs to the Rothermel spread model, plus wind reduction and rate-of-spread normalizing factors that are discussed later.

In the 1972 NFDRS, nine fuel models were provided. The users and the NFDRS technical committee wanted the number of fuel models increased in the 1978 NFDRS to supposedly improve resolution and representativeness. The researchers assigned to the project did not agree and recommended that the number of models be reduced or, at the very least, be held to nine. Their position was based on the following:

1. Fire-danger ratings are required for areas on the order of 10^4 to 10^5 acres; low on any scale of resolution.
2. It was not logical to incorporate high resolution fuel descriptors when fuel moistures and wind are resolvable at such low levels (one observation per day per 10^5 acres).
3. The information required to construct fuel models was (and still is) very limited.
4. The fire behavior prediction system developed by Rothermel and Albini (FBO package reference) and Rothermel (1983) was designed to satisfy the "1- to 100-acre/10 minutes to 1-hour resolution" fire behavior prediction needs of the fire manager.

The technical committee prevailed and the result was an array of 20 fuel models.

Eight of the nine 1972 NFDRS fuel models were retained—model F was redefined to represent intermediate age (7 to 15 years old) mixed chaparral. (The original model F represented very young stands of brush that were essentially fireproof.) Data for the original nine fuel models were taken principally from Byram (1959); Philpot (1968, 1970); Countryman and Philpot (1970); and Brown (1970a,b,c). Twelve totally new models were developed.

The selection of the twenty fuel situations to be modeled was done by the researchers subjectively. The first step was a survey of fuel types entered on fire reports by nine Forest Service Regions, the BLM, and

several State fire management agencies. A consolidated list was produced after eliminating overlaps and duplications. From that list, 20 fuel types were selected for modeling based on:

1. Significance as a fire type,
2. Interest expressed by fire managers, and
3. The availability of fuels and fire behavior data with which to develop and test the models.

Some of the fuel situations matched the assumptions of uniformity, continuity, and uniform distribution of size classes very well, and enough data existed for straightforward modeling. These fuels include the grass models (A, L, and N), slash models (I, J, and K), and the needle litter of southern plantations, western pines, and short needled conifers (P, U, G, and H). There was heavy reliance on Hough and Albini's work (1978) with the palmetto-gallberry association to put the southern rough (D) and pocosin (O) models together (D emulates a 7-year rough). The B and F models (California mixed chaparral and intermediate brush) approximate the models developed by Rothermel and Philpot (1973) and adapted by Van Gelder (1976) for FIRECAST.

The pine grass savanna (C) and sagebrush-grass (T) are combinations of grass and litter, and grass and shrubs; they violate the assumptions of uniformity and reflect art more than science.

The models constructed for Alaska—black spruce and tundra (Q and S)—are terribly artificial, but the outputs are reasonable, judging from the limited amount of fire behavior data available from Alaskan and Canadian sources.

The fuel modeling procedure incorporated a great deal of repetitive building and evaluating. As much information as possible about a particular fuel situation was gathered, but "best guesses" were used for a fuel model when nothing concrete was available. The prototype fuel model was then tested using archived fire-weather data to generate daily values of rate-of-spread and flame length. The predictions were compared to fire behavior observations, or if none were available, the results were subjectively evaluated by the researchers.

Once a preliminary set of fuel models had been developed, the fire-danger estimates produced using these models were evaluated by fire managers. The evaluation included:

1. The rate-of-spread (SC) and flame length (0.1 X BI) predictions, and
2. The seasonal profile of the NFDRS indexes, components, and live fuel moistures.

The fire-weather data sets for the field tests were specified by the evaluators. They selected a wet year, a dry year, and any other period of time that offered characteristics a fire-danger rating system should pick up.

Parameters were adjusted and the performance reevaluated several times in some cases before model parameters were settled on. Table 5 lists the 20 fuel models in the 1978 NFDRS. Fuel model parameters are summarized in appendix B. Narrative descriptions and a key for selecting an appropriate fuel model are included in the 1978 NFDRS summary publication (Deeming and others 1977).

Table 5.—List of fuel models in the 1978 NFDRS (Models A-E, G-I were included in 1972 NFDRS; model F represents a different fuel than in 1972 NFDRS)

Fuel model	General description
A	Western annual grasses
B	California mixed chaparral
C	Pine grass savanna
D	Southern rough
E	Hardwoods (winter)
F	Intermediate brush
G	Short needle pine (heavy dead)
H	Short needle pine (normal dead)
I	Heavy logging slash
J	Intermediate logging slash
K	Light logging slash
L	Western perennial grass
N	Sawgrass
O	High pocosin
P	Southern pine plantation
Q	Alaskan black spruce
R	Hardwoods (summer)
S	Tundra
T	Sagebrush-grass
U	Western long-needled conifer

DEAD FUEL MOISTURE MODELS

The dead fuel moisture models in the 1978 NFDRS are based on the theory described in section titled "Classification of Fuel Components," except when fuel moisture sticks were weighed as part of the fire-weather observation. In those cases, the 1-hour and 10-hour fuel moistures are computed using the analog stick moisture content. The 100-hour and 1,000-hour fuel moistures are computed from Fosberg's theoretical solutions, using an average equilibrium moisture content (called boundary conditions) for 24 and 168 hours, respectively. The solutions are based on two equations, one from Fosberg (1970):

$$\delta\mu/\Delta\mu = (mc - mc_0)/(\overline{EMC} - mc_0) \quad (23)$$

and equation 5 from section titled "Classification of Fuel Components":

$$\delta\mu/\Delta\mu = 1 - \zeta(\exp(-T/\tau)) \quad (5)$$

where

$\delta\mu$ is the actual moisture content change (%) in the stress period, T,

$\Delta\mu$ is the potential moisture content change (%) for the stress period T, (mc_0 − mc),

mc_0 is the moisture content (%) at the beginning of the stress period T,

mc is the moisture content (%) at the end of the stress period (T+1),

$\overline{EMC}$ is the mean equilibrium moisture content (%)for the stress period (T),

ζ is the dimensionless similarity coefficient,

τ is the fuel particle timelag (h), and

T is the simulation (stress) period timestep (h).

Repeating again, ζ is empirically derived and valid only for particular combinations of T and τ at a specific time of the day.

The 1-Hour Timelag Fuel Moisture Model

The 1978 NFDRS gives two methods to calculate the 1-hour fuel moisture, but that developed for the California wildland fire-danger rating system (USDA 1958, revised 1968) is preferable:

$$mc_1 = (4EMC + mc_{10_k})/5 \quad (\%) \tag{24}$$

where

mc_{10_k} is the age-corrected fuel stick moisture (%, see next section titled "The 10-Hour Timelag Fuel Moisture Model"), and

EMC is the equilibrium moisture content (%) calculated using the temperature and relative humidity at the fuel-atmosphere interface.

Observation time relative humidity and temperature at the fuel-atmosphere boundary layer are estimated from lapse rates determined by Haltiner (1975) that are dependent on sky cover.

To adjust standard exposed instrument readings (4.5 feet from ground in shelter) of relative humidity and temperature to fuel level, the factors in table 6 are used.

Table 6.—Fuel-atmosphere interface temperature and relative humidity adjustment factors (from Haltiner 1975)

	Fraction sky cover:sky condition			
	0.0-0.1: Clear	0.1-0.5: Scattered	0.6-0.9: Broken	0.9-1.0: Overcast
Dry bulb temperature, °F (add)	25	19	12	5
Relative humidity (multiply)	0.75	0.83	0.91	1.0

If the fuel stick moisture (mc_{10_k} is not reported, the method described by Fosberg and Deeming (1971) is used. Combining equations 5 and 23 and solving for mc_1, Fosberg's basic diffusion equation becomes

$$mc_1 = mc_o + (EMC - mc_o)(1 - \zeta(\exp(-T/\tau)) \tag{25}$$

where

mc_1 is the 1-hour timelag fuel moisture (%) at time T and

mc_o is the 1-hour timelag fuel moisture at time (T−1).

The equation was solved sequentially for forty-eight 30-minute time periods, ending at a time in the midafternoon.

Using diurnal data from the O'Neill, Nebr., experiment (Lettau and Davidson 1957), a T value of 0.5 hours, and τ and ζ values of 1.0 yielded a simplified expression for 1-hour fuel moisture for midafternoon observation time:

$$mc_1 = 1.03\ EMC\ (\%) \tag{26}$$

where EMC is the calculated equilibrium moisture content at the fuel-atmosphere interface.

The 10-Hour Timelag Fuel Moisture Model

The preferred method for obtaining 10-hour fuel moisture is from fuel moisture sticks, corrected for stick aging. When analog stick weight (W_f) is measured:

$$mc_{10} = A_1C + BC(W_f - 100)\ (\%) \tag{27}$$

with

$$A_1 = a/60 \tag{28}$$
$$B = 1 + 0.02(a/30) \tag{29}$$
$$C = C_c/4 \tag{30}$$

where

W_f is the fuel stick weight (g),
a is the number of days since the sticks were set out,
C_c is the 1978 NFDRS climate class (1 to 4), and
100.0 is the ovendry weight of the fuel sticks (g).

The age correction as developed by Haines and Frost (1978) was changed to be functional on climate class because the original function over-estimated weight loss in dry climates. NFDRS climate classes are discussed in the section titled "Live Fuel Moisture Model."

When fuel sticks are not measured, the 10-hour fuel moisture is estimated in a manner similar to that for the 1-hour fuel moisture (also reported by Fosberg and Deeming 1971).

The diurnal O'Neill, Nebr., data were used and the basic diffusion equation (eq. 25) was solved in 4-hour time steps using $\zeta = 0.87$, T = 4 hours, and $\tau = 10$ hours to produce this estimate for a midafternoon observation:

$$mc_{10} = 1.28\ EMC \quad (\%) \tag{31}$$

where

EMC is the same EMC used to calculate the 1-hour fuel moisture.

This model works well for early afternoons in strong continental areas at the approximate latitude of Nebraska in the late summer. It tends to underpredict stick readings under other conditions.

FORECASTING THE 10-HOUR FUEL MOISTURE IN AFFIRMS

Accurately forecasting the next day's 10-hour timelag fuel moisture (TLFM) requires a more complex model that utilizes 24-hour maximum and minimum temperatures and relative humidities. The 24 hours between observation times is divided into two periods: the first from the basic observation time of day 1 (1400 hours) to 0600 hours of day 2 (assumed to be the time of minimum temperature and maximum relative humidity for the 24-hour period); and the second from 0600 of day 2 to the basic observation time of day 2.

The average temperatures and relative humidities for the two periods are estimated from predictions or observations for the three occasions (times). The predicted duration of precipitation during the two periods is included in the calculation of average boundary conditions for each period:

$$D_1 = [(16 - p_{d1})EMC_1 + (2.7p_{d1} + 76)p_{d1}]/16 \tag{32}$$
$$D_2 = [(8 - p_{d2})EMC_2 + (2.7p_{d2} + 76)p_{d2}]/8 \tag{33}$$

where

D_1 is the average boundary condition for the 16-hour period from 1400 on day 1 to 0600 on day 2,

p_{d1} and p_{d2} are the precipitation durations for the two periods (h),

EMC_1 and EMC_2 are the equilibrium moisture contents for the two periods derived from average temperature andrelative humidity for each period, corrected to the fuel-atmosphere interface.

The precipitation duration effect function ($2.7p_d + 76$) is from Fosberg (1972).

The next step is to predict the 10-hour fuel moisture at the end of the first period (0600 hours) using the observed (or computed) 10-hour fuel moisture at 1400 on day 1 and D_1 as initial values. The predicted value at 0600 (day 2) then becomes the initial value for predicting the 10-hour timelag fuel moisture at 1400 on day 2:

$$mc_{10_1} = mc_{10_o} - (D_1 - mc_{10_o})(1 - 1.1 \exp(-16/10)) \quad (34)$$

and

$$mc_{10} = mc_{10_1} - (D_2 - mc_{10_1})(1 - 0.87 \exp(-8/10)) \quad (35)$$

where

mc_{10_o} is the 10-hour TLFM at 1400 of day 1,
mc_{10_1} is the 10-hour TLFM at 0600 of day 2,
mc_{10} is the forecasted 10-hour TLFM at 1400 of day 2,
0.87 in eq. 35 is the ζ derived for eq. 31, and
1.1 in eq. 34 is the ζ derived for early mornings (0600).

AFFIRMS also allows direct predictions of 10-hour fuel moistures if methods such as that by Cramer (1961) have been developed for local use. Thus, if the predicted 10-hour moisture content is entered, the computational model is skipped.

The 100-Hour Timelag Fuel Moisture Model

The 100-hour model in the 1978 NFDRS first computes a 24-hour average boundary condition as an input to the basic diffusion equation. The boundary condition is determined from precipitation duration, maximum and minimum temperature, and relative humidity, and is for the 24-hour period from observation time on day 1 to observation time on day 2. When some of the above observation elements are missing (principally in FIRDAT), cruder methods are used for 100-hour timelag fuel moisture computations (Cohen and Deeming, in preparation).

The similarity coefficient (ζ) in the 1978 model was selected to produce the same solution as would the 1972 model, when the precipitation duration is 24 hours. The boundary condition is

$$D = [(24 - p_d)\overline{EMC} + (0.5p_d + 41)p_d]/24 \quad (36)$$

and the basic diffusion equation becomes

$$mc_{100} = mc_{100_o} + (D - mc_{100_o})(1 - 0.87 \exp(-24/100)) \quad (37)$$

where

D is the 24-hour average boundary condition (%),

$\overline{EMC}$ is a weighted 24-hour average equilibrium moisture content (%), calculated from the day's maximum and minimum temperatures and relative humidities (see below),

p_d is the precipitation duration for the 24-hour period, and

mc_{100_o} and mc_{100} are the observed and predicted 100-hour timelag fuel moistures for observation times at days 1 and 2, respectively.

The 1978 computerized 100-hour timelag fuel moisture model calculates the 24-hour average equilibrium moisture content (EMC, %) more effectively than in the 1972 NFDRS. The manual 1978 NFDRS (and the entire 1972 system) calculate EMC using arithmetic averages of a day's maximum and minimum temperature, and maximum and minimum relative humidity.

The 1978 computerized NFDRS derives EMC for both the 100-hour and 1,000-hour timelag fuels from a weighted average of two EMC's: one calculated from the day's maximum temperature and minimum relative humidity (EMC_{min}), and a second calculated from the day's maximum relative humidity and minimum temperature (EMC_{max}).

Weighting is based on day length, which improves seasonal response of NFDRS fuel moisture models. As day length shortens, nighttime conditions (EMC_{max}) are given more weight, thus promoting moisture recovery in the 100-hour and 1,000-hour timelag fuels. Conversely, as day length increases, daytime conditions (EMC_{min}) are given more weight, thus promoting additional moisture loss in the heavier fuels.

Under this scheme the weighted EMC is calculated by:

$$EMC = [(n)EMC_{min} + (24 - n)EMC_{max}]/24 \quad (38)$$

where n is the hours of daylight (refer to appendix D for computational details and NFDRS index response).

Manual calculation of the 100-hour timelag fuel moisture in the 1978 NFDRS is simpler than in the 1972 method because no arithmetic is necessary (both systems assume a constant 24-hour mean temperature to simplify the calculations). Using average relative humidity and precipitation is a compromise, but it does retain most of the calculated moisture response.

There are three types of missing data that are considered in the 100-hour fuel moisture computations. If only precipitation duration is missing, it is estimated by:

$$p_d = (p_a + 0.02)/p_r \quad (39)$$

rounded to the nearest whole hour, where

p_d is the precipitation duration (limited to a maximum of 8 hours),

p_a is the 24-hour precipitation amount (inches), and

p_r is 0.25 inch/h for climate classes 1 and 2, and 0.05 inch/h for climate classes 3 and 4.

If extreme values for relative humidity are missing, but temperature extremes are available, maximum and minimum relative humidities are estimated by assuming the air mass does not change over the 24 hours and the specific humidity is constant. The day's observation time relative humidity is combined with the day's temperature extremes to estimate relative humidity extremes (Cohen and Deeming, in preparation).

If daily temperature extremes are missing, EMC_{min} is assumed to be the observation time EMC, and EMC_{max} is a climate class dependent default value. For climate

classes 1 and 2, EMC_{max} is 15 percent; for classes 3 and 4, it is 23 percent.

The weighted EMC is then computed from equation 38; the daily boundary condition from equation 36; and the 100-hour moisture content from equation 37.

The 1,000-Hour Timelag Fuel Moisture Model

The 1,000-hour timelag fuel moisture model retains the basic format of the 100-hour model, but requires an assessment of the average boundary conditions for 7 days or 168 hours instead of 24 hours (Fosberg and others 1981). A 7-day interval was chosen so that the calculation would be done the same day each week in the manual version.

The mean 7-day boundary value (D, %):

$$D = (D_1 + D_2 + ... + D_7)/7 \quad (40)$$

is computed from the 24-hour average boundary values (day length weighted) for the previous 7 days:

$$D_n = [(24 - p_{dn})EMC_n + (2.7p_{dn} + 76)p_{dn}]/24 \quad (41)$$

where n denotes the n^{th} day and EMC_n is weighted as described in the 100-hour model.

The diffusion equation then becomes

$$mc_{1000} = mc_{1000_o} + (mc_{1000_o} - D)(1 - 0.82 \exp(-168/1{,}000)) \quad (42)$$

where

mc_{1000} is the predicted 1,000-hour fuel moisture,
mc_{1000_o} is the initial value from 7 days prior,
D is the 7-day average boundary condition (%), and
0.82 is the derived ζ value.

In manual calculations, the 7-day change in 1,000-hour timelag fuel moisture is calculated with a nomogram and manually added to (or subtracted from) the 1,000-hour timelag fuel moisture from 7 days previous. This arithmetic is not buried in the nomogram because the 7-day change is a variable needed for input into the NFDRS live fuel moisture model. As a result, the 1,000-hour timelag fuel moisture must be calculated for all fuel models in spite of the absence of 1,000-hour fuels in many. The computer version does this bookkeeping automatically.

RESPONSE TO DROUGHT

By itself the 1,000-hour timelag fuel moisture is a good indicator of the severity of a medium term (4- to 6-month) drought event. The 1,000-hour timelag fuel moistures calculated using data from different climate classes showed minimum values during recent drought years to be characteristic of the climate class. The following tabulation summarizes some cases studied:

Location	Year	Season minimum 1,000-hour timelag fuel moisture,%
Walport, Oreg.	1973	21
Fort Meyers,Fla.	1970	14
Ely, Minn.	1976	11
Bonners Ferry, Idaho	1973	9
Lytle Creek, Calif.	1972	5

As another example, the following tabulation portrays the frequency of seasonal minimum 1,000-hour timelag fuel moisture values at Ninemile, Mont., for the years 1965–75. In 1966 and 1967, both very severe fire years, the 1,000-hour TLFM dropped to 9 percent.

Season minimum 1,000-hour TLFM (%)	Frequency
9	2
10	0
11	0
12	3
13	4
14	1
15	1

LIVE FUEL MOISTURE MODELS

Improvements in the Rothermel (1972) fire model made it possible to treat live fuel more realistically in the NFDRS update. Live fuels can now act as either a heat sink or heat source. Live fuels become a heat source when their moisture content drops enough to allow dessication and ignition during dead fuel combustion. If their moisture content remains above a critical level (live fuel moisture of extinction), live fuels do not burn but act as a heat sink (Albini 1976a).

The live fuel moisture model provides more analytical and consistent estimates of live fuel moisture, replacing the herbaceous vegetation transects required by the 1972 NFDRS. The following section draws heavily upon Burgan (1979).

Although it is not based on rigorous principles of plant physiology, the live fuel model broadly approximates the moisture content of living herbaceous plants, and the leaves and twigs of small woody shrubs.

In the original live fuel model proposed by Rothermel, plant moisture was treated as a function of the Keetch-Byram (1968) drought index. Several empirical factors required to control plant response to drying and wetting, however, could not be derived for all climates.

Development of the 1978 NFDRS led to the discovery that the 1,000-hour timelag fuel moisture function responded to wetting and drying cycles similar to those expected for live fuel. Thus, the 1,000-hour timelag fuel moisture serves as the basic meteorological factor for calculating live woody fuel moisture and is used in a modified form to emulate the wetting and drying cycles of live herbaceous fuels.

Plants adapted to various moisture regimes respond differently to rainfall anomalies: those adapted to moist environments lose moisture faster during drought than those from dry environments. The 1978 live fuel moisture model, therefore, provides drying rates by climate class.

Although the United States can be divided into many climatic zones, four classes were judged adequate to provide the broadscale plant moisture responses needed for rating fire danger. These four climate classes are adapted from Thornthwaite's (1931) earliest climate

classification system. Arid and semiarid provinces are grouped into a single class; true desert is of little practical concern to fire management. And when considering fire behavior, the subhumid province belongs to the humid province rather than the dry, subhumid province. The climate class descriptions, general geographic areas to which they apply, and the vegetative characteristic of each are provided in table 7. Figure 6 maps the climate classes for the contiguous United States and Alaska.

Climate class defines different linear drying rates for annuals, perennials, and woody plants, but within a particular climate class, a single drying rate is assumed for live woody plants throughout a growing season. In live herbaceous plants, drying occurs in two stages: green stage when herbaceous moisture is above 120 percent, and transition stage when moisture is between 120 and 30 percent. In the green stage both annuals and perennials dry at the same rate, but in the transition stage annuals exhibit faster drying rates than perennials.

The endpoints of the drying curves are required to define drying rates. First, weather data from several locations within each climate class were used to plot seasonal 1,000-hour timelag fuel moisture profiles. Typical plant moistures for each climate class and vegetation type (woody, annual, and perennial) were then matched with these profiles. Because measurements of seasonal moisture variation in woody and herbaceous plants were not generally available from different regions of the United States, the live fuel model was calibrated to produce reasonable moisture values. Table 8 shows the specific performance objectives.

Maximum live fuel moistures were chosen to be 250 percent for herbaceous fuels and 200 percent for live woody shrubs, at 25 percent 1,000-hour timelag fuel moisture. Towards the lower end of the moisture scale herbaceous plants were considered cured at 30 percent moisture content and woody plants dormant if their moisture content dropped to 50 percent. The minimum

Table 7.—The 1978 NFDRS climate classes (from Deeming and others 1977)

NFDRS climate class	Thornthwaite (1931) humidity province	Characteristic vegetation	Regions
1	Arid	Desert (sparse grass and scattered shrubs)	Sonoran deserts of western Texas, New Mexico, southwest Arizona, southern Nevada, and western Utah; and the Mojave Desert of California.
	Semiarid	Steppe (short grass and shrubs)	The short grass prairies of the Great Plains; the sagebrush steppes and pinyon-juniper woodlands of Wyoming, Montana, Idaho, Colorado, Utah, Arizona, Washington, and Oregon; and the grass steppes of the central valley of California.
2	Subhumid (rainfall deficient in summer)	Savanna (grasslands, dense bush, and open conifer forests)	The Alaskan interior; the chaparral of Colorado, Arizona, New Mexico, the Sierra Nevada foothills, and southern California; oak woodland of California; ponderosa pine woodlands of the West; and mountain valleys (or parks) of the Northern and Central Rockies.
3	Subhumid (rainfall adequate in all seasons)	Savanna (grasslands and open hardwood forests)	Blue stem prairies and blue stem-oak-hickory savanna of Iowa, Missouri, and Illinois.
	Humid	Forests	Almost the entire eastern United States; and those higher elevations in the West that support forests.
4	Wet	Rain forest (redwoods, and spruce-cedar-hemlock)	Coast of Northern California, Oregon, Washington, and southeast Alaska.

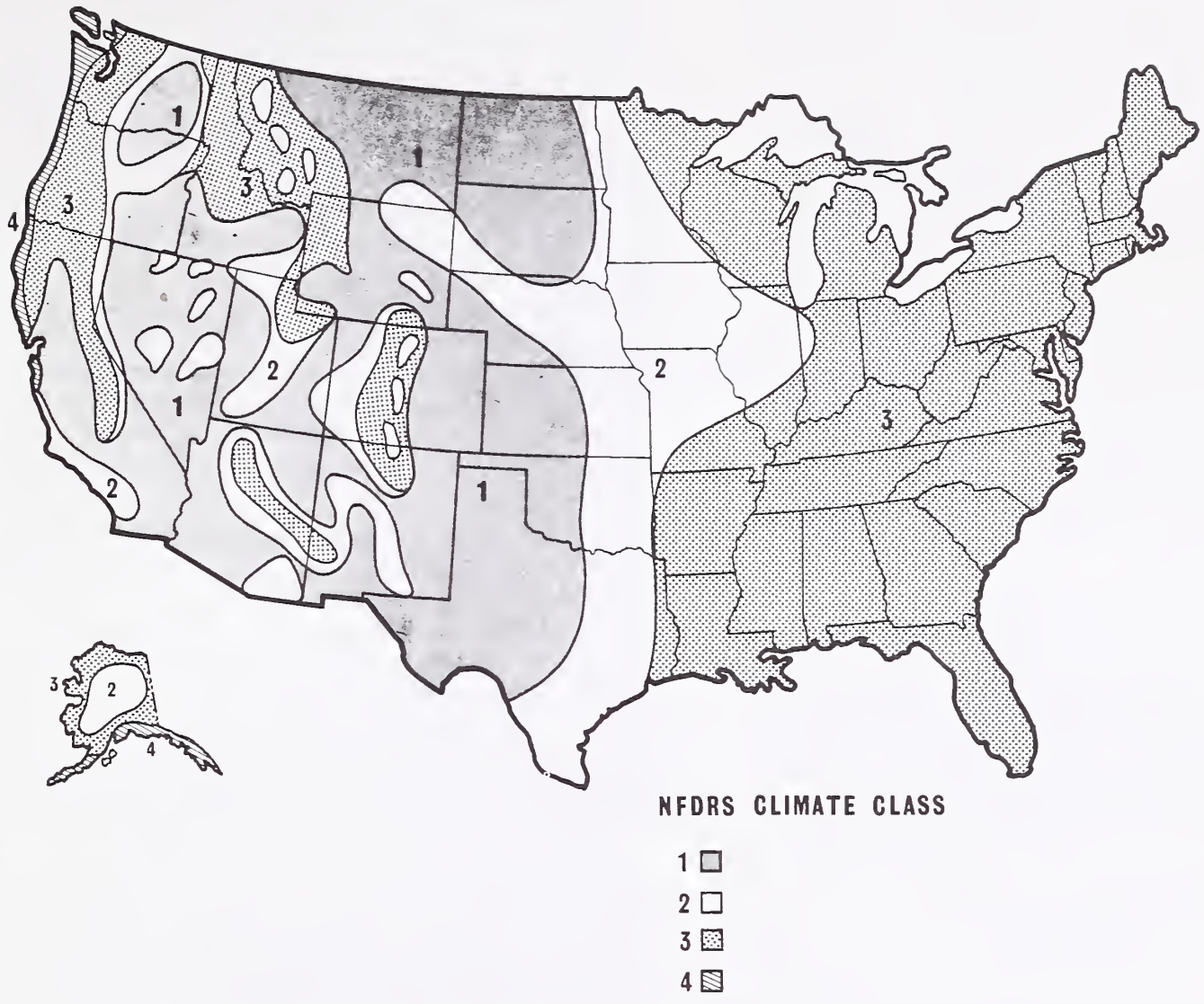

Figure 6.—1978 NFDRS climate class (from Deeming and others 1977, p. 5).

Table 8.—Minimum allowable moisture content of live fuels in live fuel models (from Burgan 1979)

Type of season	Grasses and forbs		Shrubs, twigs, and foliage
	Annuals	Perennials	
	Percent		
Wet	30 (Late cure)	>80	>110
Normal	<30	50-80	80-100
Dry	<30 (Early cure)	<50	50-80

woody and herbaceous moistures were matched with typical minimum 1,000-hour timelag fuel moistures and minimum X1,000-hour values, respectively, for each climate class. Table 9 provides the slopes and intercepts of the drying curves for each climate class.

A dynamic live fuel moisture algorithm simulates greening and curing of herbaceous fuels by transferring fuel load between the live herbaceous class and the 1-hour timelag class as the herbaceous fuel moisture varies between 30 and 120 percent during the growing season.

Rothermel provided the empirical data used for development and initial testing of the live fuel moisture model. He used the xylene distillation technique for determining moisture content to construct profiles of herbaceous and woody plants near Missoula, Mont., during the 1975 and 1976 fire seasons. Developed to emulate these particular moisture profiles, the model was then adjusted to produce reasonable profiles for the rest of the United States.

Herbaceous Fuel Moisture

Although relating herbaceous fuel moisture directly to the 1,000-hour timelag fuel moisture proved reasonable for periods of drying, excessive fuel moisture recovery was predicted during periods of precipitation. A function was developed to decrease at the same rate as the 1,000-hour timelag fuel moisture, but to increase more slowly.

During the growing season this value is

$$X_{1000} = X_{y1000} + k_1 k_2 (\Delta mc_{1000}) \qquad (43)$$

where

X_{1000} is the day's live fuel moisture recovery value, (%),
X_{y1000} is yesterday's X_{1000} value, (%),
k_1 is a drying/wetting factor (dimensionless),
$k_1 = 1$ if $\Delta mc_{1000} < 0$ (drying regime)
$k_1 = 0.0333(mc_{1000}) + 0.1675$ otherwise
k_2 is a temperature factor (dimensionless),
$k_2 = 1.0$,
if the day's average temperature > 50 F (10° C)
$k_2 = 0.6$,
if the day's average temperature ≤ 50 F (10° C)
Δmc_{1000} is the 24-hour change in mc_{1000} (%).

k_1 limits the increase in herbaceous fuel moisture due to precipitation. It is scaled to allow the X_{1000} value to duplicate the 1,000-hour timelag fuel moisture when the 1,000-hour timelag fuel moisture is 25 percent or more.

k_2 reduces the response of the X_{1000} value to compensate for plants' slower physiological processes during cool weather. Figure 7 compares the 1,000-hour timelag moistures with the X_{1000} value.

Prior to spring green-up, herbaceous fuel is assumed to be completely cured, letting herbaceous fuel moisture (mc_h) equal the 1-hour TLFM.

During spring green-up, live herbaceous fuel moisture increases gradually from the 1-hour timelag fuel moisture. The live fuel model accommodates gradual green-up at the request of eastern United States users who feared that the instantaneous green-up originally proposed would not properly reflect the transition from high fire danger in early spring to low fire danger in summer. The green-up period length varies linearly from 7 days for climate class 1 to 28 days for climate class 4. The length of green-up was scaled to climate class because plants growing in drier climates typically respond more quickly to favorable growing conditions than plants in wetter climates.

When a spring flush of growth becomes generally apparent, the user specifies the beginning of green-up. Herbaceous fuel moisture is then calculated according to the equation:

$$mc_h = mc_1 + gu[(a_h + b_h X_{1000}) - mc_1] \qquad (44)$$

where

a_h and b_h are climate-dependent intercept and slope for annuals or perennials from table 9,
X_{1000} is the fuel moisture recovery value from eq. 43,
mc_1 is the 1-hour timelag fuel moisture, and
gu is the elapsed fraction of the green-up period.

If a second green-up occurs during the growing season, the X_{1000} value is again set equal to the 1,000-hour timelag fuel moisture. The same green-up procedure is followed, except herbaceous moisture increases from its current value instead of the 1-hour timelag fuel moisture.

After the green-up period is complete (gu = 1.0), the herbaceous fuel moisture is

$$mc_h = a_h + b_h X_{1000} \ (y = a + bx). \qquad (45)$$

Table 9.—Regression slopes and intercepts for drying rates of live fuels (from Burgan 1979)

Fuel	Climate class 1 Slope	1 Intercept	2 Slope	2 Intercept	3 Slope	3 Intercept	4 Slope	4 Intercept
Woody fuels	7.5	12.5	8.2	-5.0	8.9	-22.5	9.8	-45.0
Herbaceous fuels								
Annuals and perennials - green stage	12.8	-70.0	14.0	-100.0	15.5	-137.5	17.4	-185.0
Annuals - transition stage	18.4	-150.5	19.6	-187.7	22.0	-245.2	24.3	-305.2
Perennials - transition stage	7.4	11.2	8.3	-10.3	9.8	-42.7	12.2	-93.5

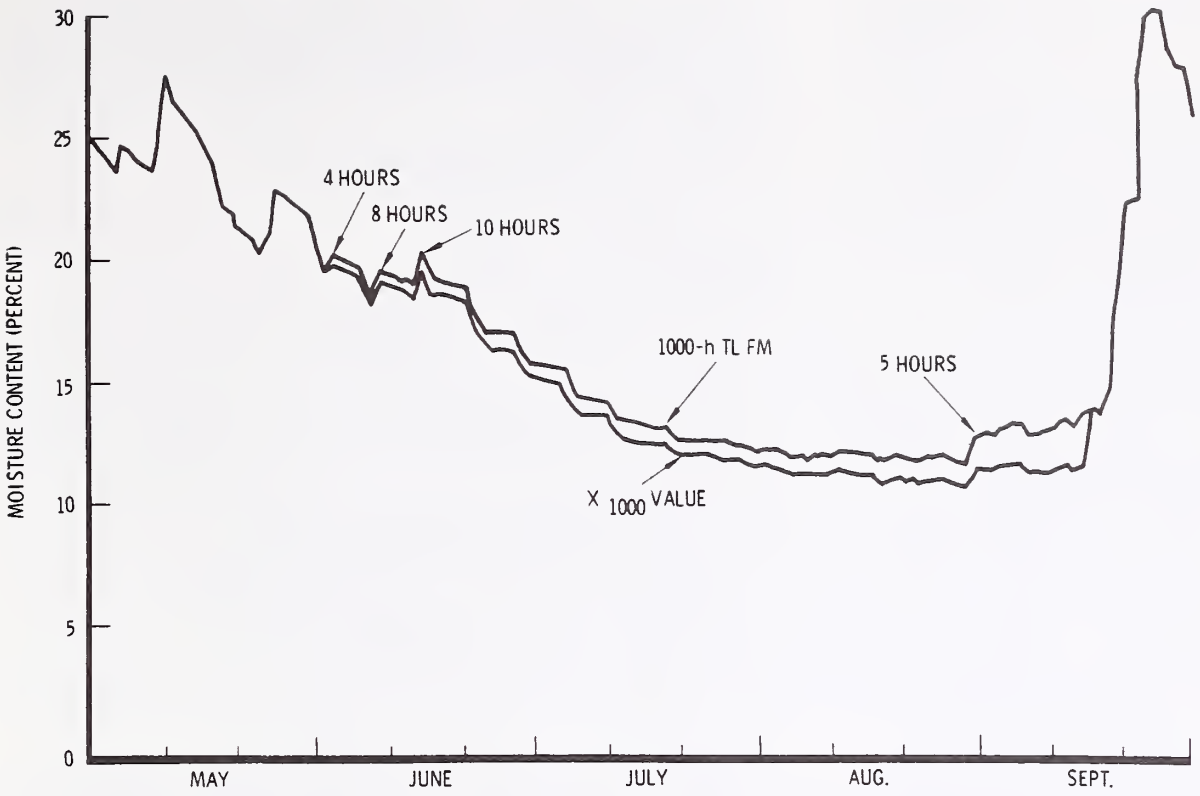

Figure 7.—Comparison of X_{1000} to 1,000-hour values in live fuel moisture model (from Burgan 1979, p. 8).

When the user specifies that the herbaceous vegetation has cured phenologically, or frozen, herbaceous fuel moisture again equals the 1-hour timelag fuel moisture. A freeze occurs at or below a minimum temperature of 25° F, or when minimum temperatures between 32° and 26° F occur five times.

Figure 8 illustrates the relationship between the X_{1000} value and the annual and perennial herbaceous moistures.

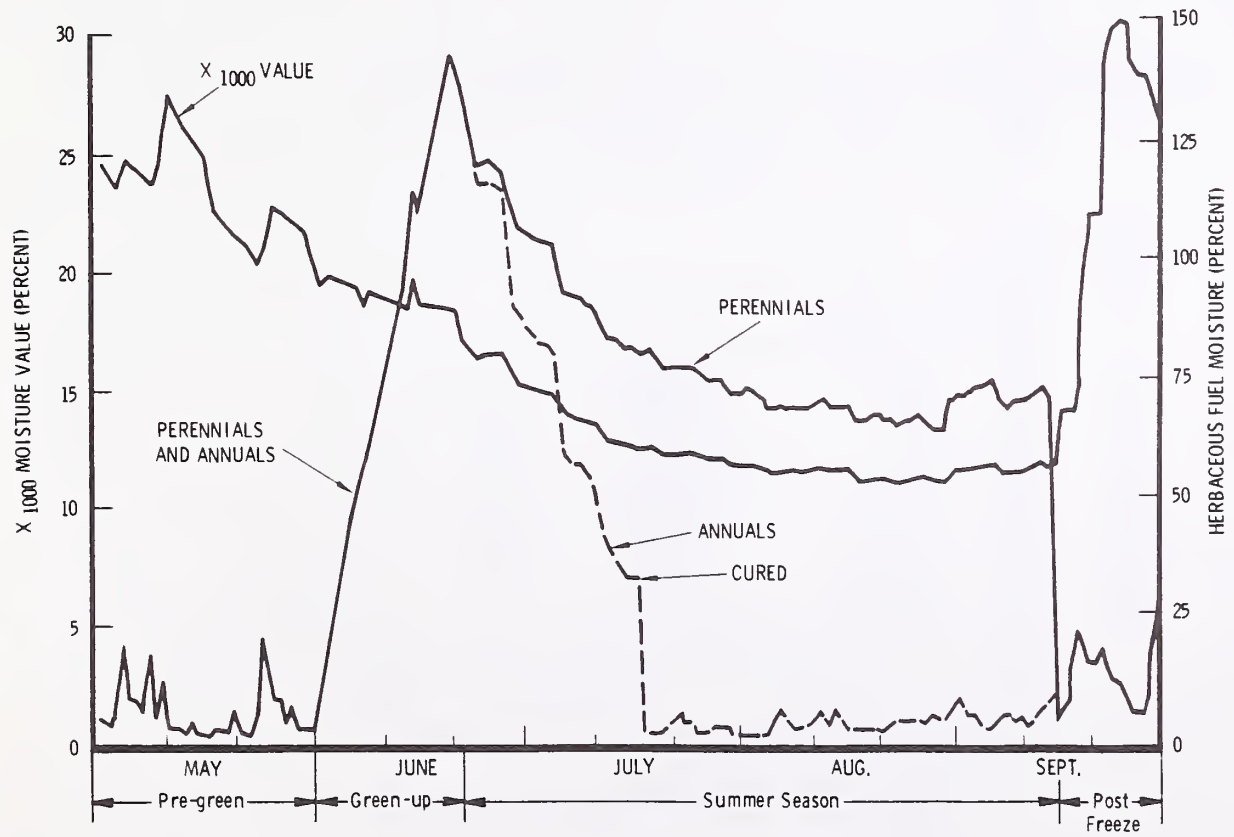

Figure 8.—An example season trace of X_{1000} and live herbaceous fuel moisture values (from Burgan 1979, p. 9).

TRANSFER OF FUEL BETWEEN LIVE AND DEAD CATEGORIES

Before green-up the entire herbaceous fuel load falls under the 1-hour class. During green-up the live herbaceous fuel load transfers from the 1-hour to the live fuel category as herbaceous moisture increases from 30 to 120 percent. At levels greater than 120 percent the herbaceous fuel load reaches its maximum, and the 1-hour timelag fuel load its minimum.

As herbaceous plant moisture decreases later in the growing season and varies between 30 and 120 percent, the load of perennial herbaceous fuels is shifted between the live and dead fuel categories. This indicates a transition stage. One hundred and twenty percent approximates the upper limit for transition, roughly defining the moisture content at which new growth is complete and foliage mature. Thirty percent was chosen as the lower limit because it approximates the fiber saturation point, below which herbaceous plants are assumed dead.

The process differs slightly for annual herbaceous plants. Following green-up the model does not allow the moisture content of annuals to increase. The fuel load for annuals transfers from the live category to the dead category, never in the reverse direction, as allowed with perennials. At 30 percent moisture content (after phenological curing or following a freeze in the fall), all the herbaceous fuels have been added back to the 1-hour timelag class.

The fuel load transfer equations are:

$$W_{1hd} = W_{1h} + W_h f \quad (46)$$

$$W_{hg} = W_h(1 - f) \quad (47)$$

where

$f = -0.0111mc_h + 1.33$ and $0 \leq f \leq 1.0$

and

W_{1hd} is the total load of 1-hour timelag fuel, including dead herbaceous fuel transferred to the 1-hour timelag category,

W_{1h} is the load of the 1-hour timelag fuel before inclusion of any cured herbaceous material,

W_h is the total load of herbaceous fuel,

f is the fraction of the herbaceous fuel that is to be transferred to the 1-hour timelag class,

W_{hg} is the load of herbaceous fuel that is still green, and

mc_h is the herbaceous fuel moisture.

Figure 9 shows herbaceous fuel load changes in relation to moisture content changes.

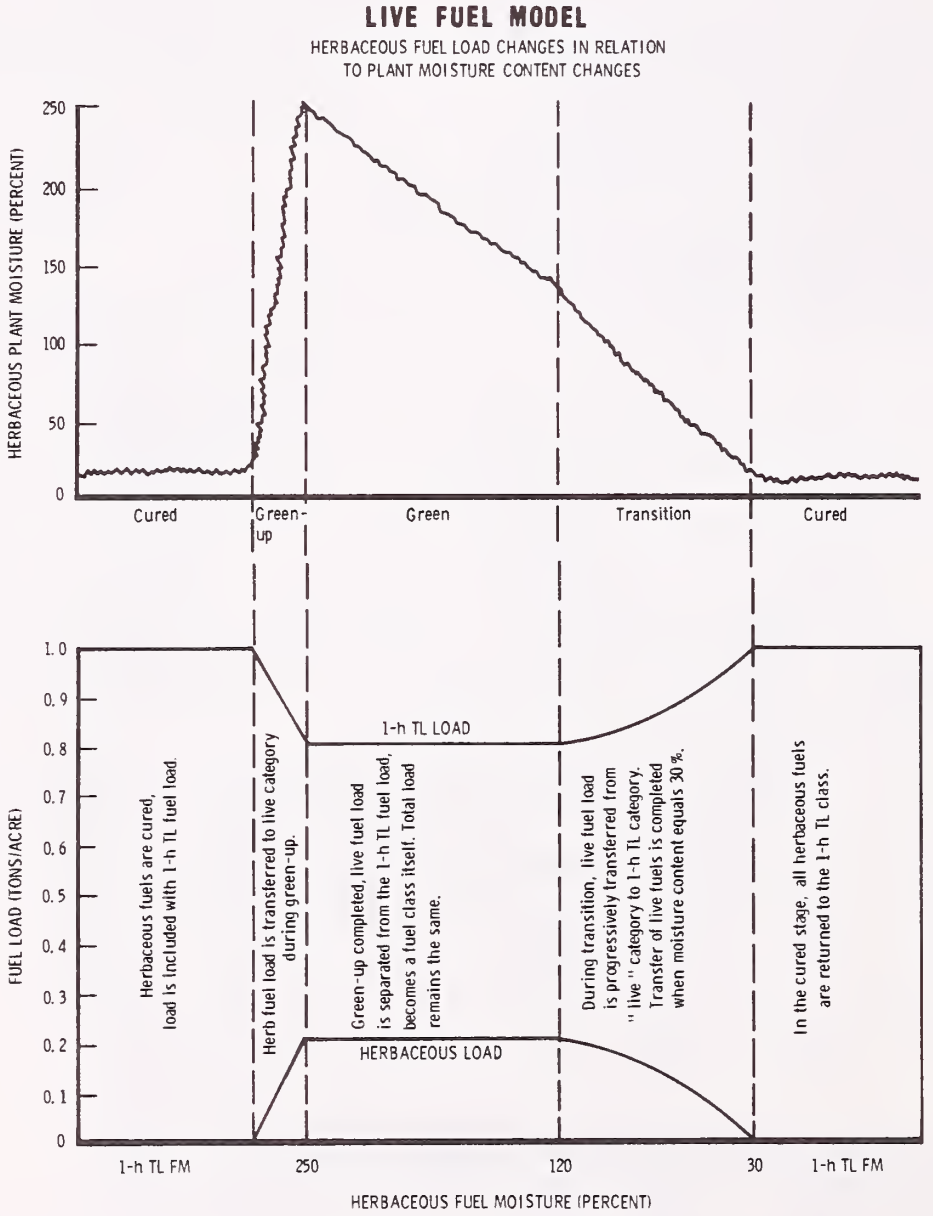

Figure 9.—Stylized live fuel moisture model load transfer function (from Burgan 1979, p. 11).

Figures 10 and 11 give examples of fuel transfer between live and dead categories for perennial and annual grasses. Herbaceous moisture will typically approach 250 percent at completion of green-up, but given a dry spring or late green-up, herbaceous moistures peak at lower values.

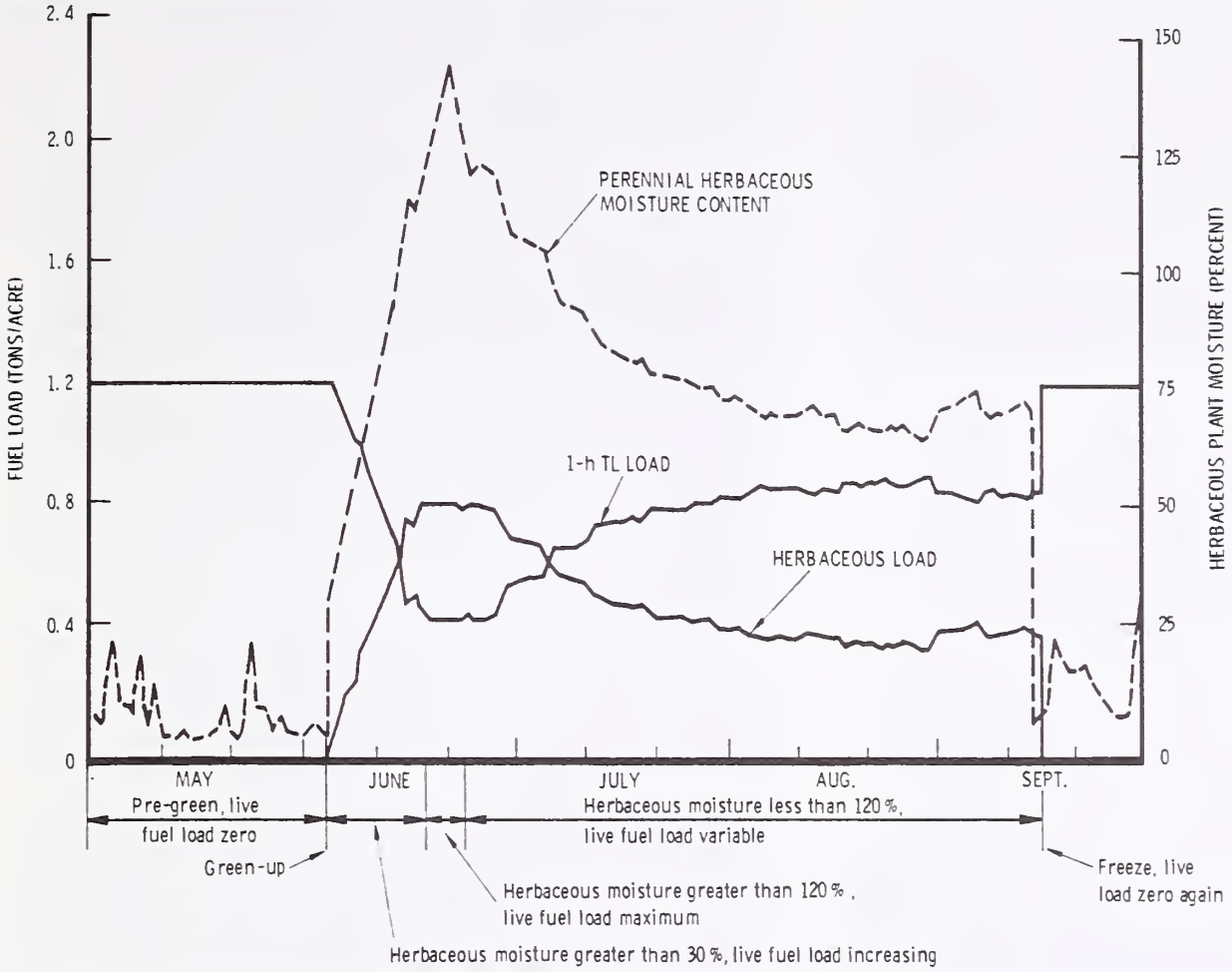

Figure 10.—Typical seasonal trace of live fuel moistures and resulting 1-hour load transfer between dead and live categories for perennial herbaceous fuels (from Burgan 1979, p. 12).

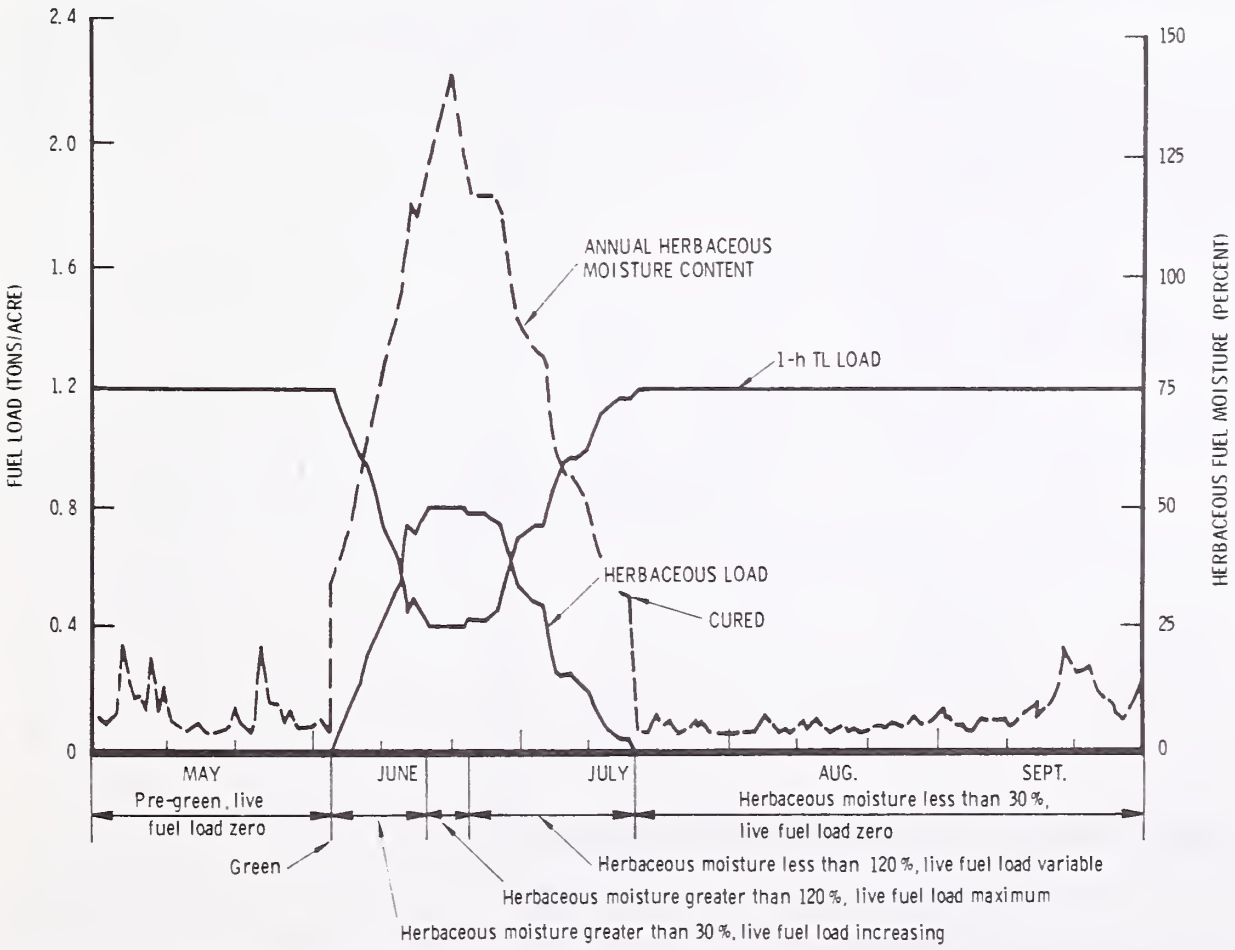

Figure 11.—Typical seasonal trace of live fuel moistures and resulting 1-hour load transfer between dead and live categories for annual herbaceous fuels (from Burgan 1979, p. 13).

Woody Fuel Moisture Model

Prior to spring green-up, woody shrubs are assumed dormant, and the woody fuel moisture (mc_w) held constant. Measurements of chamise leaf moisture in southern California indicate minimum values for woody plants in climate class 2 is about 60 percent (Dell and Philpot 1965). Similarly, measurements in the Southwest suggest a minimum woody moisture content of 70 percent for climate class 3 (Blackmarr and Flanner 1968). Pregreen mc_w values are defined as 50, 60, 70, or 80 for climate classes 1, 2, 3, or 4, respectively. During spring green-up, woody moisture gradually increases from the pregreen minimum:

$$mc_w = mc_{wo} + gu[(a_w + b_w mc_{1000}) - mc_{wo}] \quad (48)$$

where

mc_{wo} is the pregreen minimum moisture,
a_w and b_w are climate-dependent intercept and slope from table 9,
mc_{1000} is the 1,000-hour timelag fuel moisture, and
gu is the fraction of the green-up period that has elapsed.

If a second green-up occurs during a growing season, woody fuel moisture increases from its current value instead of from the pregreen value.

After green-up completion (gu = 1) woody fuel moisture is

$$mc_w = a_w + b_w mc_{1000}. \quad (49)$$

When the shrubs become dormant, woody fuel moisture is set back to the minimum value specified by the climate class. Figure 12 illustrates a typical woody fuel moisture profile and its relationship to 1,000-hour timelag fuel moisture.

FIRE BEHAVIOR MODEL

The Rothermel (1972) mathematical fire model provided an excellent method for systematically integrating fuels, weather, and topographic information to determine potential fire behavior, hence fire danger, in a homogeneous fuel bed.

The fire behavior portion of the NFDRS consists of the spread component (SC) and the energy release component (ERC). Using relationships developed by Byram (1959) and Albini (1976b), these components are combined in the burning index (BI). The BI reflects the potential containment problem presented by a single fire. It is linearly related to the predicted flame length at the head of a fire.

The fire model predicts fire spread and intensity in homogeneous fuel, based solely on static fuel and environmental properties assessed prior to ignition, not dynamic fire variables such as temperature, heat fluxes, and induced winds.

By using weighting factors assigned to the various fuel sizes, the fire model can accept heterogeneous fuel arrays composed of various-sized fuel particles. By weighting various parameters, attributes of heterogeneous fuel arrays are characterized for the fuel bed. Thus, while a particular fuel bed may have four dead fuel components, each with its own surface area-to-volume ratio, it has a singular "characteristic" surface area-to-volume ratio and "characteristic" fuel moisture, dependent on the weighting factors. The assumption of horizontal and vertical fuel continuity (and thus a uniform packing ratio and bulk density) throughout the bed is maintained.

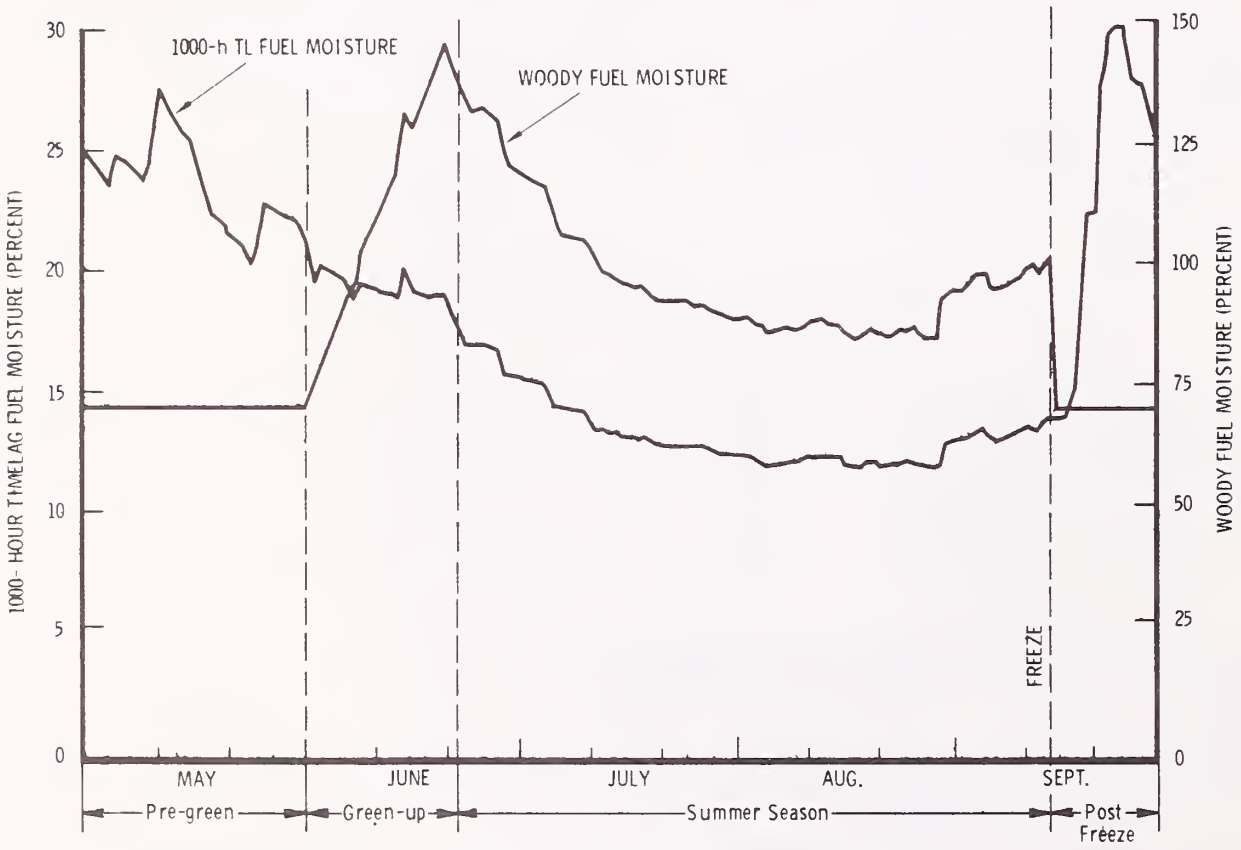

Figure 12.—A typical woody fuel moisture profile and its relationship to the 1,000-hour timelag fuel moisture (from Burgan 1979, p. 14).

Fire Model Parameter Weighting

Fuel arrays consist of particles of various sizes, some live and some dead. A method of weighting surface area-to-volume ratios (σ) and fuel moisture content (m_f) was developed to synthesize these varied parameters into a single, characteristic value for use in the fire model.

Rothermel (1972) introduced surface-area weighting for calculation of rate of spread. Weighting fuels by surface area eliminated making arbitrary decisions about which fuel sizes to include and which not to include as fire model inputs. A singular characteristic parameter is determined by weighting parameters in a fuel array composed of a mixture of particle sizes.

The concept of a unit fuel cell facilitates understanding of fuel size-class distribution. A unit fuel cell is the smallest volume of fuel within a stratum of mean depth that has sufficient fuel to statistically represent fuel in the entire complex. Now define:

$\bar{A}_T$ as the mean total surface area of fuel per unit fuel cell,

$\bar{A}_i$ as the mean total surface area of fuel of i^{th} category perunit fuel cell, and

$\bar{A}_{ij}$ is the mean total surface area of fuel of j^{th} size class and i^{th} category per unit fuel cell,where

i is the fuel category (dead = 1, living = 2), and

j is the fuel size class (1 = 1-hour, 2 = 10-hour, etc.).

The mean total surface area per unit fuel cell of each size class with each category is determined from the mean loading of that size class and its surface-area-to-volume ratio and particle density:

$$\bar{A}_{ij} = (\bar{\sigma}_{ij}\bar{W}_{ij})/\bar{\varrho}_p. \quad (50)$$

The mean total surface area of the i^{th} category per unit fuel cell and the mean total surface area per unit fuel cell are then obtained by summing the areas within each category and within the fuel cell with equations 51 and 52:

$$\bar{A}_i = \sum_{j=1}^{3} \bar{A}_{ij} \quad (51)$$

$$\bar{A}_T = \sum_{i=1}^{2} \bar{A}_i. \quad (52)$$

Two weighting parameters are then calculated and used to weight fuel particle, fuel bed, and moisture content parameters throughout the fire spread model:

$$f_{ij} = \bar{A}_{ij}/\bar{A}_i \quad (53)$$

$$f_i = \bar{A}_i/\bar{A}_T \quad (54)$$

FIRE BEHAVIOR COMPONENTS

Spread Component (SC)

In the 1978 NFDRS, SC is numerically equivalent to the predicted rate of spread, rounded to the nearest whole number. The SC algorithm is the unmodified Rothermel fire spread model, with the fuel elements weighted by surface area:

$$SC = kR \quad (55)$$

where

k is a SC scaling factor (1.0 min/ft), and

R is the predicted rate of spread (ft/min).

WIND AND SLOPE IN THE 1978 NFDRS

Windspeed and slope enter into the Rothermel rate-of-spread equation through coefficients functional upon wind, slope, and fuel bed properties. Windspeed measured at the 20-foot level (10-minute average) is reduced to midflame height (as required for rate-of-spread computations) through a wind reduction factor.

Wind Reduction Factors

Ratios of the windspeed at roughly the midflame height to the 20-foot standard height were calculated for grass, shrub, and timbered areas assuming a standard logarithmic wind profile. Using variable roughness lengths, the ratios fell within the range of 0.4 to 0.6.

As such, wind reduction factors were made a fuel model parameter. For the grass-type fuel models, 0.6 is used. For the shrub and brush fuel models 0.5 is used; and for the timber fuel models the midflame windspeed is 0.4 of the 20-foot windspeed. The wind factor (ϕ_w) is then calculated as described by Rothermel (1972, eqs. 47−50).

Slope Classes

The slope classes in the 1978 NFDRS were selected so the slope coefficient (ϕ_s) would double from one class to the next higher class (slope class 5 has 16 times the effect [2^4] on rate of spread as slope class 1). Using a 90 percent slope for the slope class 5 midpoint, the slope factor (ϕ_s) for class 5 was computed from Rothermel's (1972) equation 5l. The class 4 ϕ_s was then computed by halving; class 3 by quartering; class 2 by taking one-eighth; and class 1 by taking one-sixteenth of the class 5 ϕ_s value.

The 1978 NFDRS slope classification scheme is summarized in table 10.

Table 10.—1978 NFDRS slope classes

NFDRS Slope class	Slope range	Effective class midpoint	Slope coefficient
	----------*Percent*----------		
1	0-25	22.5	0.267
2	26-40	31.8	.533
3	41-55	44.5	1.068
4	56-75	63.6	2.134
5	>75	90.0	4.273

Energy Release Component (ERC)

When the 1972 NFDRS was being developed, it was recognized that more than rate of spread of a potential fire had to be considered. Unfortunately, there are no models as definitive as the Rothermel model to quantify the effects of the condition of large fuels and the lowest layers of duff and litter on the fire behavior and fire management problem. There is no way that a fire-danger rating system would be acceptable if the ratings were solely based on the condition of fine fuels, which is the effect of surface-area weighting of fuel model parameters.

The authors decided that the spread component calculations should be totally consistent with rate-of-spread calculations in the Rothermel model; rate of spread is dominated by the condition of fine fuels. The approach selected to bring larger fuels into play was straightforward: use the fuel energy computations of the spread model—the reaction intensity—but base the influences of the different classes of fuel on their contribution to the total fuel load. Specifically, for the energy release component, the characteristic surface area-to-volume ratio and weighted fuel moisture of the fuel bed would be calculated using fuel class weighting factors based on loading, not surface area as in the spread component. This solution had no experimental basis.

For the 1978 revision it was hoped that work being done by Frank Albini with large fuel burnout would provide a concrete approach to the fuel energy problem. Unfortunately, Albini was not satisfied with the results of his effort and recommended that the 1972 loading-weighted approach be retained. Rothermel agreed with Albini, so with that counsel the 1972 procedure was retained.

Another decision made during the development of 1972 NFDRS was to change the form of the moisture-damping coefficient used in calculating the ERC. The curve form of this coefficient as developed by Rothermel is S-shaped. It declines rapidly with increasing fuel moisture at low fuel moistures and at moisture contents near the moisture of extinction; it is relatively flat in the midrange of fuel moistures. Again, a judgment was made: to develop and use a moisture-damping function that did not have the flattened "shoulder." The function,

$$\eta_e = 1 - 2(mc) + 1.5(mc)^2 - 0.5(mc)^3 \quad \text{(dimensionless)} \tag{56}$$

where

mc is the ratio of the load-weighted characteristic fuel bed moisture to the moisture of extinction (a damping coefficient is computed for both the dead and live fuel components),

was developed by Fosberg to assure a continuing increase in the ERC as fuel moistures in the midrange decreased. This function is used only for ERC computations, not spread component which uses

$$\eta = 1 - 2.59(mc) + 5.11(mc)^2 - 3.52(mc)^3 \tag{57}$$

which was developed by Rothermel. This function was retained in the 1978 NFDRS.

There was one significant change made to the ERC in the 1978 version that should be noted. The 1972 version computed ERC from a scaled loading-weighted reaction intensity (I_{Re}, Btu/ft²-min):

$$ERC_{72} = j(I_{Re}).$$

In the 1978 version the residence time, τ_r, as defined by Anderson (1969) was included to make the ERC relatable to the total energy released per square foot during the flaming combustion stage (residence time):

$$ERC_{78} = k(I_{Re})(\tau_r) \tag{58}$$

where

k is a scaling factor (0.04 ft²/Btu),

I_{Re} is the loading-weighted reaction intensity (Btu/ft²-min), and

$$\tau_r = 384/\sigma \text{ (min)} \tag{59}$$

where σ is the surface area-weighted characteristic surface area-to-volume ratio of the fuel bed. This change was made for several reasons:

1. In the 1972 NFDRS τ_r was introduced at the point where the burning index (BI) was calculated. Since τ_r is fuel model dependent, a separate table to calculate the BI was required for each fuel model. Combining τ_r with I_{Re} made only one BI table necessary in the manual version.

2. Available heat per unit area, E:

$$E = \tau_r(I_{Re}) \text{ (Btu/ft²)} \tag{60}$$

is more understandable and easier to relate to than reaction intensity.

3. Heat per unit area rather than another intensity-based index is more consistent with the original idea of a fuel energy phase as proposed by Keetch.

Burning Index (BI)

The 1978 burning index is the scaled predicted flame length, as calculated from the loading-weighted reaction intensity (I_{Re}), the surface area-weighted rate of spread (R), and the surface area-weighted residence time. A flame length relationship developed by Byram (1959):

$$F_L = 0.45(I)^{0.46} \tag{61}$$

where I is the fireline intensity (Btu/ft²-min), was modified by Albini (1976a), and used to estimate flame length from which the BI is computed. The equation for flame length now incorporates the spread component and available energy (E):

$$F_L = j[(R/60)(I_{Re})(\tau_r)]^{0.46} \quad \text{(ft)} \tag{62}$$

$$F_L = j[(SC/60)(25(ERC))]^{0.46} \quad \text{(ft)} \tag{63}$$

where

R is the rate of spread (ft/min),

I_{Re} is the load-weighted reaction intensity (Btu/ft²-min),

τ_r is the flaming residence time (min),

1/60 is a unit conversion (1 min/60 s), and

j is a coefficient (0.45 ft²-sec/Btu).

Consequently,

$$BI = j_1 F_L \tag{64}$$

where j_1 is the BI scaling factor (10/ft).

IGNITION COMPONENT, RISK, AND OCCURRENCE INDEXES

The occurrence indexes, in conjunction with the burning index, compute the cumulative fire load index. The two fire occurrence indexes, man-caused (MCOI) and lightning-caused (LOI), give daily projections of the number of reportable man-caused and lightning-caused fires per million acres of protected land. Occurrence index values range from 0 to 100 and are scaled such that a value of 100 indicates an expected fire density of 10 fires/million acres.

The MCOI is a function of the ignition component (IC) and the man-caused risk: LOI is a function of a weighted IC and lightning-caused risk. Risk factors are the average expected number of firebrands on a given day by source (lightning- or man-caused). Determined from empirical models, risk factors allow users to compute scaling factors to adjust the risk models to specific regions (see Deeming and others 1977).

The IC is the probability that a reportable fire will result from a firebrand.

MCOI, tenfold the expected number of reportable man-caused fires per million acres on a given day, is

$$MCOI = IC(R_{MC}) \tag{65}$$

where R_{MC} is related to the total number expected man-caused firebrands for the day. Similarly, the LOI, or tenfold the number of reportable lightning fires per million acres for a given day is defined by:

$$LOI = IC(R_L) \tag{66}$$

where R_L is related to the number of expected lightning strokes.

Common to both MCOI and LOI, development of the IC will be reported first, followed by a discussion of the 1978 NFDRS risk models.

Ignition Component

The ignition component is calculated from the probability of ignition, P(I), the day's spread component, SC, and the maximum probable spread component SC_{max}. The SC_{max} is a fuel model parameter, calculated under a set of severe burning conditions (appendix B). This differs from the 1972 NFDRS ignition component, which was simply equal to the probability of ignition. The 1972 version of ignition probability used a moisture of extinction of 30 percent.

PROBABILITY OF IGNITION, P(I)

P(I) is the probability that a firebrand will start a fire (reportable or not) after landing on receptive fuels. This differs from the IC, which incorporates burning conditions (via the SC) to estimate the probability of a firebrand becoming a reportable fire. The P(I) predicts only whether the firebrand has sufficient energy to produce a successful ignition and is taken from an office report prepared by Mark Schroeder in 1969. Its development is included here because of its importance in the system's occurrence indexes and general unavailability. It is presented in original form of metric units.

The first step in determining P(I) is calculating the heat required to bring a fine fuel particle with a given mc_1 from its initial temperature to ignition temperature, the heat of preignition (Q_{ig}).

Heat of preignition (Q_{ig}, cal/g) is calculated by summing the following quantities:

A. The heat required to raise the temperature of the dry fuel from its initial temperature, T_o, to its ignition temperature, T_i (assumed to equal 320 °C),

B. The heat required to raise the moisture contained in the fuel from its initial temperature to the boiling point,

C. The heat of desorption,

D. The heat required to vaporize the moisture, and

E. The heat required to raise the temperature of water vapor contained in the fuel voids from the boiling point to ignition temperature.

The quantities are referred to as Q_a,Q_b, Q_c, Q_d, and Q_e, respectively.

To compute Q_a for a gram of fuel, the specific heat of dry fuel, c_f, is multiplied by the temperature range $T_i - T_o$. According to Stamm (1964), c_f varies with the temperature:

$$c_f = 0.266 + 0.00116T \tag{67}$$

where T is the average temperature between the ignition and initial temperatures. Thus

$$c_f = 0.266 + 0.00116(320 + T_o)/2$$
$$= 0.4516 + 0.00058T_o \tag{68}$$

and

$$Q_a = (T_i - T_o)(0.4516 + 0.00058T_o). \tag{69}$$

Calculating Q_b requires the temperature change from T_o to 100° C, multiplied by the mass of water and the specific heat (1.0 for water):

$$Q_b = m_f(100 - T_o) \text{ (cal/g)} \tag{70}$$

where m_f is the moisture content of the fuel (fraction).

Heat of desorption, Q_c, is the heat required to separate the bound water from the fibers, and equals the heat given off (heat of adsorption) when water vapor is adsorbed. From Stamm's (1964) figure 12−1, the following equation may be approximated:

$$Q_c = 280 \exp(-15.1m_f) \quad \text{(cal/g)}. \tag{71}$$

The total heat of desorption is obtained by integrating from m_f to m_f=0:

$$Q_c = 280 \int_0^{m_f} \exp(-15.1m_f)dm_f \tag{72}$$

$$Q_c = -18.54 \exp(-15.1m_f)\Big|_0^{m_f} \tag{73}$$

$$Q_c = 18.54(1 - \exp(-15.1m_f)) \quad \text{(cal/g)}. \tag{74}$$

The heat required to vaporize the moisture is the heat of vaporization times the mass of water:

$$Q_d = 640m_f. \tag{75}$$

Q_e, the heat required to raise water vapor in the voids from the boiling point to ignition temperature, was calculated to be negligible compared to Q_a, Q_b, Q_c, and

Q_d, and is omitted. Thus

$$Q_{ig} = Q_a + Q_b + Q_c + Q_d, \text{ or}$$

$$Q_{ig} = 144.51 - 0.266T_o - 0.00058T_o^2 - T_o m_f + 18.54(1 - \exp(-15.1m_f)) + 640m_f \text{ (cal/g)}. \quad (76)$$

Schroeder then proposed that if a firebrand lands on receptive fuels the probability of ignition as a function of Q_{ig} should be the product of the probability that a firebrand of a specific size will cause an ignition and the probability that the firebrand will be that size. The latter probability is dependent on the size distribution of firebrands, but this information was lacking. Schroeder used the findings of Blackmarr (1972) for the probability that a specific size firebrand will cause an ignition. This turned out to be reverse S-shaped curves (fig. 13) for slash pine litter at different moisture contents. To generalize this solution, Schroeder first defined a critical moisture content at P(I) = 0 for a specific firebrand, above which no ignition will take place. Using equation 76, he converted moisture content to Q_{ig} at a constant temperature. Defining Q_f as the heat from a firebrand at the critical moisture content and assuming that, at the critical moisture content, Q_f was equal to Q_{ig}, he transposed the curve to show P(I) as a function of $Q_f - Q_{ig}$.

Schroeder next reasoned that because firebrand size distributions were unknown one might deduce the distribution by knowing the shape of the $P(I/Q_{ig})$ curve. A clue as to the shape of this curve could be obtained from previous studies. John Keetch, in a circular letter dated April 19, 1960, reported on his survey of ignition studies used in fire-danger rating systems in various parts of the country. These were based on man-caused fire occurrence frequency and fine fuel moisture. He found considerable agreement among the studies. Figure 14 is a mean curve on log paper for these studies, with the highest value of ignition probability set at 1.5 percent moisture content. Some information on the size distribution of firebrands was desired to be contained in the index, but not the entire spectrum of firebrand sizes. Rather only those that caused ignition were included. Lacking any information as to where the truncation point might be, Schroeder arbitrarily set the lowest value of fuel moisture used at the 50 percent cumulative probability, replotted the curve from figure 14 on log-probability paper, and found that a straight line fit the data fairly well. At the same time he converted moisture content to Q_{ig} at constant temperature using equation 76.

The mathematical problem of backtracking from probability of ignition for a specific firebrand and the Q_{ig} curve to find the size distribution of firebrands turned

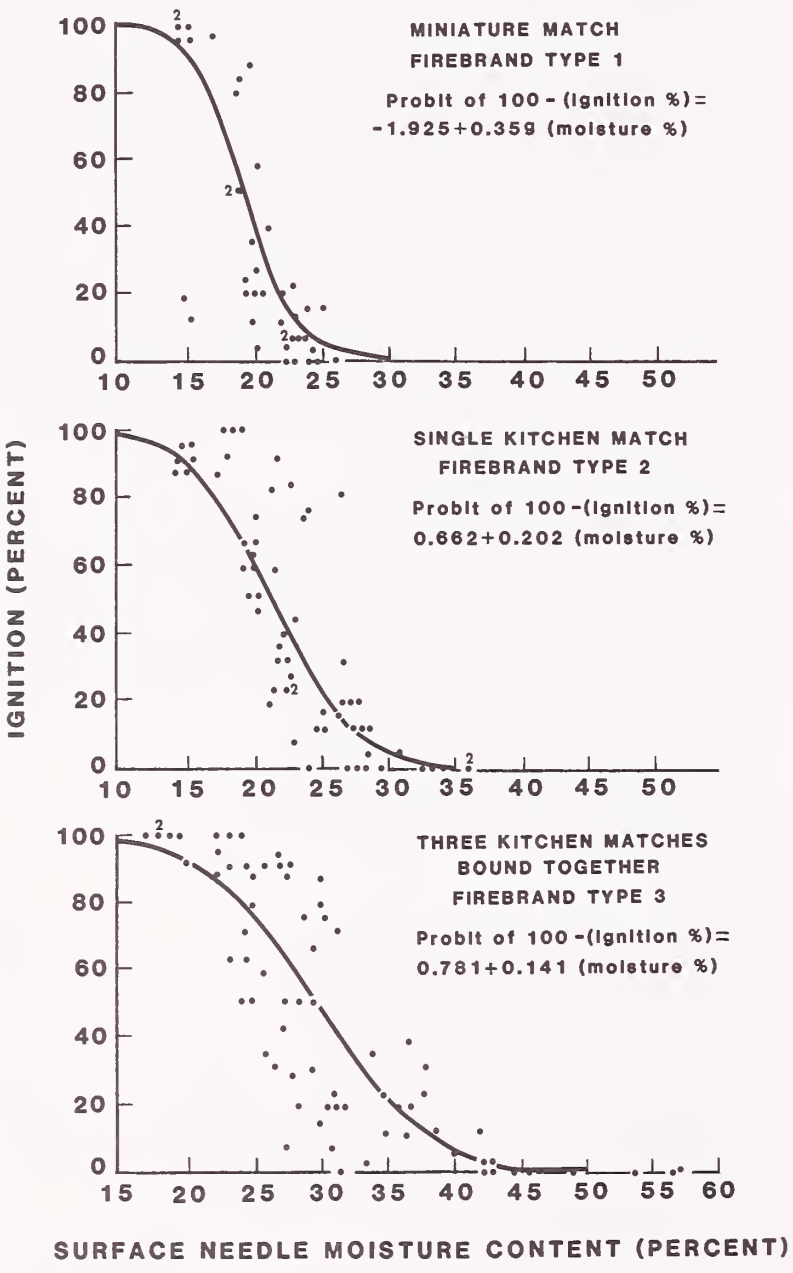

Figure 13.—Probability of ignition curves as a function of moisture content for three firebrand sizes (from Blackmarr 1972).

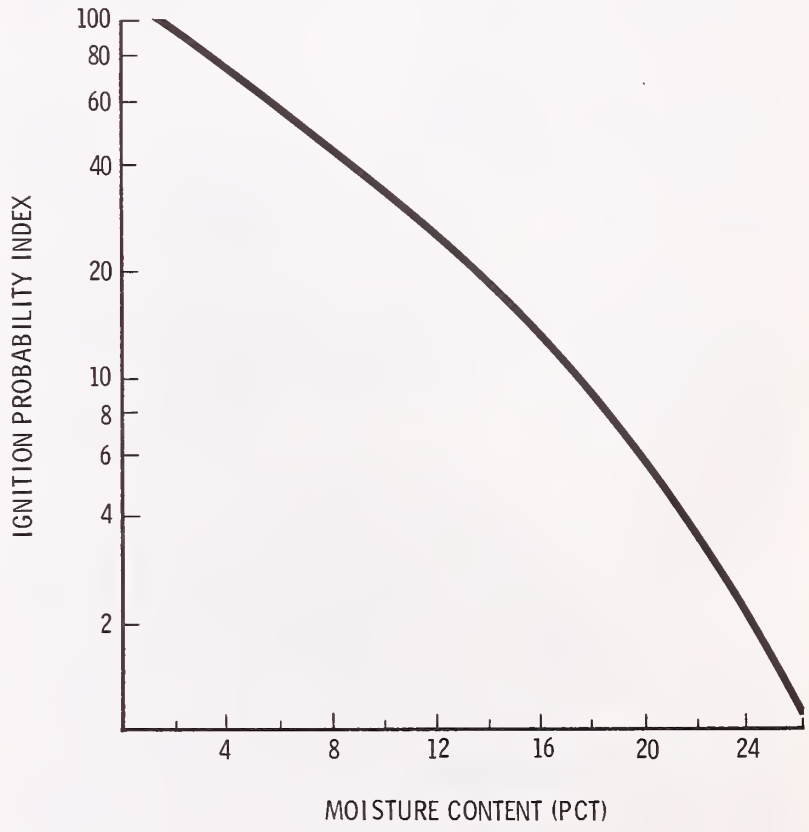

Figure 14.—Ignition probability as a function of dead fuel moisture content (from Schroeder 1969).

out to be intractable, and the effort was abandoned. Instead, the useful portion of the straight line function on the log-normal plot was solved numerically, yielding:

$$P(I/Q_{ig}) = 0.000048\chi^{4.3}/50 \quad (77)$$

where

$$\chi = (400 - Q_{ig})/10. \quad (78)$$

The general form of this equation is

$$P(I/Q_{ig}) = (k_3\chi^{k_4})/50.0 \quad (79)$$

where

$\chi = (Q_{igmx} - Q_{ig})/10$,
k_3 and k_4 are empirical constants,
Q_{igmx} is the heat or preignition for a fuel particle at the extinction moisture content, and

k_3, k_4, and Q_{igmx} are functions of the dead moisture of extinction.

Table 11 shows some computed values of k_3, k_4, and Q_{igmx} for various values of m_{xd}. The 1978 NFDRS uses the k_3 and k_4 values associated with $m_x = 25$ and $Q_{igmx} = 344$, although Schroeder developed the P(I) using $m_x = 30$ percent and $Q_{igmx} = 380$. The reason for this change was because the 30 percent used in the 1972 NFDRS was felt to be too high. An m_x of 20 percent was first proposed, but a value of 25 percent was finally used for the 1978 version.

The P(I) function is calibrated with other constants, P_1 and P_2, such that P(I) = 0 when $mc_1 = m_x = 25$, and P(I) = 100 when $mc_1 = 1.5$ percent. Table 11 shows other possible values of P_1 and P_2.

Ignition component is then computed from a function developed by Bill Main at the North Central Experiment Station. Using pooled data from Jackson (1977):

$$IC = P(I)(0.1)(SC_N)^{0.5} \quad (80)$$

where

$$SC_N = SC/SC_{max}\cdot 100 \text{ (maximum } SC_N = 100), \quad (81)$$

$$P(I) = (P(I)' - 0.00232)(100)/0.99767, \quad (82)$$

$$P(I)' = (0.000923\chi^{3.66})/50, \quad (83)$$

$$\chi = (344 - Q_{ig})/10, \quad (84)$$

and

SC is the day's spread component,
Q_{ig} is computed from equation 76,
$P_1 = 0.00232$,
$P_2 = 0.99767$,
$k_3 = 0.000923$, and
$k_4 = 3.66$.

This IC is used directly in calculating daily values of the MC0I, and weighted with a rain-influenced IC for calculating the daily LOI (section titled "Lightning Risk Model and Lightning Occurrence Index").

Man-Caused Risk Model

Jackson (1977) presented a model for predicting the average number of reportable man-caused fires for a given ignition component value:

$$E(\text{number of fires}) = IC(d)(d_1)(d_2)(A) \quad (85)$$

where d, d_1, and d_2 are empirically derived coefficients that tune the model to a particular protection unit, and A is the protection unit area in millions of acres. Jackson developed the model using fire occurrence data from Forest Service Region 9 (Eastern). Data from Region 3 (Southwest) were used for testing the model. The reported R^2 value was 0.89 for the tested area.

Equation 85 is normalized to millions of acres by dividing by A:

$$E(\text{number of fires}/10^6 \text{ acres}) = IC(d)(d_1)(d_2). \quad (86)$$

The MCOI is scaled such that 10 fires per million acres results in an MCOI value of 100, or:

$$MCOI = 10\ E(\text{number of fires}/10_6 \text{ acres}) \quad (87)$$

Combining equations 86 and 87 yields

$$MCOI = 10(IC)(d)(d_1)(d_2) \quad (88)$$

and by letting $d_o = 10d$, the expression becomes:

$$MCOI = IC(d_o)(d_1)(d_2). \quad (89)$$

But the desired final form of the equation is

$$MCOI = IC(R_{MC}/100) \quad (90)$$

so combining equations 89 and 90 yields:

$$MCOI = IC(d_o)(d_1)(d_2) = (IC)(R_{MC})/100. \quad (91)$$

Table 11.—Normalization constants for probability of ignition as a function of moisture of extinction and heat of ignition

Moisture of extinction (m_X, %)	Heat of ignition (Q_{ige}, Btu)	Constants			
		k_3	k_4	P_1	P_2
15	268	0.082164	2.58	0.01553	0.98446
20	306	.008379	3.15	.00554	.99446
25	344	.000932	3.66	.00232	[1].99767
30	381	.000120	4.11	.00050	.99950
35	425	.0000124	4.58	.00072	.99928
40	470	.00000135	5.02	.00052	.99948

[1]Used in the 1978 NFDRS IC.

Solving for R_{MC} yields:

$$R_{MC} = 100(d_o)(d_1)(d_2). \quad (92)$$

Coefficients d, d_o, d_1, and d_2 are area and unit (Region, Forest, or District) dependent. A Regional scaling factor, d, equals the historical number of man-caused fires per million acres, per day, per unit of ignition component for an entire region over a 5-year base period. Expressed numerically, it equals the slope of the regression (forced through zero) of the number of fires per million acre-days on the daily IC for the parent (regional) unit. An acre-day is the acreage of the regional protection unit multiplied by the number of fire-weather days in the 5-year analysis. The parent protection unit should be at least 10 million acres in size, with 300 or more man-caused fires per year. Recalling that:

$$d_o = 10d$$

d_o will generally range between 0.05 and 1.00.

d_1, a man-caused risk scaling factor, accounts for differences in risk between the parent unit (Region) and the protection unit (Forest or District). It serves as an input to both the AFFIRMS and FIRDAT processors.

d_1 is the ratio of the total number of fires on the protection unit divided by the product of the average IC value, area of the protection unit (10^6 acres), and the number of fire-weather days, all divided by the total number of fires on the parent unit divided by the product of the average IC value and the total acres in the parent unit and the total number of fire-weather days in the parent unit.

$$d_1 = \frac{\sum (\text{fires}_u)/\overline{IC}_u\ A_u\ n_u)}{\sum (\text{fires}_r)/(\overline{IC}_r\ A_r\ n_u)} \quad (93)$$

where

subscripts u and r denote the protection unit and parent region, respectively,

(fires) is the total number of man-caused fires for the computational period,

$\overline{IC}$ is the average daily IC (man-caused) for the period,

A is the area in millions of acres, and

n is the total days used in computing the IC values.

A correction factor, d_2, flows from a subjective evaluation of the activity level of the principal risk sources of man-caused fires on a protection unit. d_2 is partitioned by day of the week and the eight statistical fire causes available from standard fire report forms. d_2 adjusts for short-term fire problems (such as arson) or predictable changes in man-caused risk (weekend, holidays, hunting season, etc.):

$$d_2 = d_j/25 \quad (94)$$

where d_j is the unnormalized R_{MC} defined by:

$$d_j = \sum_{i=1}^{8} R_{ij} \quad (95)$$

where R_{ij} is the partial man-caused risk of source i (of the eight standard statistical fire causes) on day j of the week, and

$$R_{ij} = R_{SRij}G_{ij} \quad (96)$$

where R_{SRij} is the risk source ratio for day j of the week.

$$R_{SRij} = 7 \sum_{i=1}^{8} \sum_{j=1}^{7} \text{fires}_{ij}/\text{fires}_u \quad (97)$$

and G_{ij} is the risk (number of firebrands) associated with the daily activity level assigned by the fire manager to risk source i on day j.

Values of G for daily activity levels are presented in the following tabulation:

Daily activity level	G_{ij}
Extreme	100
High	50
Normal	25
Low	12
None	0

Deeming and others (1977) and Burgan and others (1977) detail computation of d, d_o, d_1, and d_2, burying most of the arithmetic in nomograms.

Man-caused risk (R_{MC}) determined from nomograms is used to calculate the daily MCOI from equation 90:

$$MCOI = (IC)R_{MC}/100. \quad (98)$$

The average number of fires for the protection unit then becomes

$$E(\text{number of fires}) = (MCOI)A(\text{millions of acres})/10. \quad (99)$$

APPLYING MAN-CAUSED RISK

The severity of man-caused fire problems on a protection unit dictates the level of man-caused risk assessment. For example, a complete analysis, with eight risk sources and a separate set of daily risk source ratios, R_{ij}, for each month may be needed for high man-caused fire areas such as southern California or southern Georgia. At the other extreme, managers of areas such as White Mountain National Forest in New Hampshire, which averages fewer than 10 fires per year, gain little by partitioning risk source ratios. In such situations all risk sources may be combined and it will be an unnecessary complication to stratify by day of week, month, or even season. Between the two extremes lies an approach that can tailor man-caused risk assessment to match the magnitude of the problem.

Lightning Risk Model and Lightning Occurrence Index

The lightning occurrence index (LOI) is an average estimate of the number of reportable lightning-caused fires per million acres protected:

$$LOI = IC_W R_L \quad (100)$$

where IC_W is the day's weighted lightning-caused ignition component, and R_L is an estimate of fire-starting lightning strikes in a rating area.

The 1978 NFDRS lightning-caused fire occurrence index model is based on an approach described by Fuquay and others (1979). The development of the LOI departed from Fuquay's model at the point where the probability of ignition of a lightning-caused fire is computed. For the sake of simplicity, the 1978 NFDRS IC was used

rather than Fuquay's P(I). The two methods were compared, and the resulting difference was judged to be within the range of uncertainty of the Fuquay model.

Lightning-caused risk (R_L) is a function of several meteorological parameters grounded in the lightning activity level (LAL). R_L is calibrated to a locality by a lightning risk scaling factor (K), which compensates for not using the Fuquay lightning ignition model. The lightning risk scaling factor is empirically derived from archived lightning-caused fire occurrence and lightning activity level data. The lightning risk scaling factor is required because of the differences between local fuel types in their susceptibility to ignition by lightning. Thunderstorms, amounts of rain, and lightning discharge characteristics also differ among regions. The Fuquay lightning ignition model was derived using thunderstorm data from northwestern Montana and northern Idaho.

The LAL is an index (forecasted, observed, and verified) of thunderstorm activity on a scale from 1 to 6 for a 2,500-mi² rating zone. Table 12 tabulates typical thunderstorm attributes for the six LAL's. Four typical storm characteristics have been designated for each LAL from 2 through 5. Lightning level 1 signifies no thunderstorms, and LAL 6 indicates a special condition involving high-level dry thunderstorms.

Table 12.—Thunderstorm attributes for lightning activity levels (adapted from Fuquay and others 1979)

Lightning activity level	Clouds and storm development	Rel. freq. on T/S days (%)	Fraction of area covered by radar echoes of indicated strength				Percent of area receiving less than the amount of rain indicated			
			Very light	Light	Moderate	Heavy	O-T	<0.1''	<0.3''	<0.9''
	Typical Cloud and Precipitation Conditions (2,500 mi² or 6 500 km² area)									
1	No thunderstorms[1]		No radar echoes				No precipitation			
2	Few building cumulus only occasionally reaching cumulus congestus stage; single cumulonimbus in forecast area. Visual tops: <30,000 ft (9 100 m) m.s.l.	10	0.1	<0.1			90	91	100	
3	Scattered cumulus to cumulus congestus; widely scattered cumulonimbus clouds; cloud-to-ground lightning averaging 1-2 per min max.	35	.2	.2	0.05		70	90	98	100
4	Growing cumulus and cumulus congestus stage over 0.1-0.3 of the area; scattered cloud-to-ground lightning in area averaging 2-3 per min max.	35	.2	.1	.05		65	80	95	100
5	Cumulus congestus common over area, occasionally obscuring the sky; moderate to heavy rain associated with cumulonimbus clouds light to moderate rain preceding and following lightning activity. Lightning flashes occurring steadily at some place in or during storm period; maximum cloud-to-ground flash rate greater than 3 per min.	18	.3	.1	.05	0.02	50	75	85	100
6	Scattered towering cumulus with a few at thunderstorm stage; very limited horizontal extent; high bases (15,000 to 17,000 ft m.s.l.). Virga in most prominent hydrometeor form. Lightning flash rate is low, averaging less than 1-3 per 5-min period each storm.[2].	<2								

Lightning - Amount and Rate

Lighting activity level	Maximum radar echo height, m.s.l.		Cloud-to-ground (CG) lightning per 2,500 mi² (6 500 km²	Occurance rates, maximum		
				CG/5 min	CG/15 min	Ave. rate/min
	Feet	*Meters*				
2	<28,000	<8,500	20	—	—	—
3	26,000-32,000	7,900-9,700	40	0-10	0-17	1-2
4	30,000-36,000	9,100-11,000	80	4-19	6-32	2-3
5	>36,000	>11,000	160	9-32	19-77	3

[1]In most general terms, 2 days out of 3 will not be thunderstorm days during a typical fire season in the mountainous areas of the western continental United States

[2]Used with red-flag warnings of extreme fire activity.

LAL 6 conditions, although rare (fewer than 2 percent of thunderstorm days), often present extremely severe fire problems. They occur when sufficient moisture and instability for thunderstorm development are found only upwards from approximately 15,000 feet (mean sea level). Virtually no wetting precipitation reaches earth (it evaporates—often producing strong and erratic downdrafts), but lightning is still present. When an LAL of 6 is forecast, a red flag or equivalent alert is usually issued. For NFDR purposes R_L and LOI are both set at 100.

The four storm characteristics grounded in LAL's 2 through 5 are:

1. Number of cloud-to-ground lightning discharges per storm (S_{cg}),
2. Ground area covered by radar echoes—rain area (s_s),
3. Area intensity of rainfall, and
4. Total storm size (s_{dl}).

Forming an idealized storm (fig. 15), these and other parameters allow calculation of total cloud-to-ground lightning strikes over a rating area. The racetrack with an infield concept pictures a large lightning area encompassing a smaller rain and lightning area. This storm moves according to upper level winds (u_w) and rain falls over a fraction of the total storm area. The probability of ignition, P(I), is reduced in the rainfall area due to wetting of fine fuels. Table 13 depicts typical storm characteristics by lightning activity level. The adaptation of the model to the 1978 NFDRS assumes a constant storm speed of 30 miles per hour ($u_w = 30$) in the computation of other storm attributes.

Precipitation duration (p_d) is computed from the length of the rainfall band (s_s, mi) and the rate of storm movement (u_w):

$$p_d = s_s/u_w. \quad (101)$$

Storm duration (s_d) is computed from an empirically derived function dependent on cloud-to-ground strikes (S_{cg}):

$$s_d = -86.83 + 153.41(S_{cg})^{0.1437}. \quad (102)$$

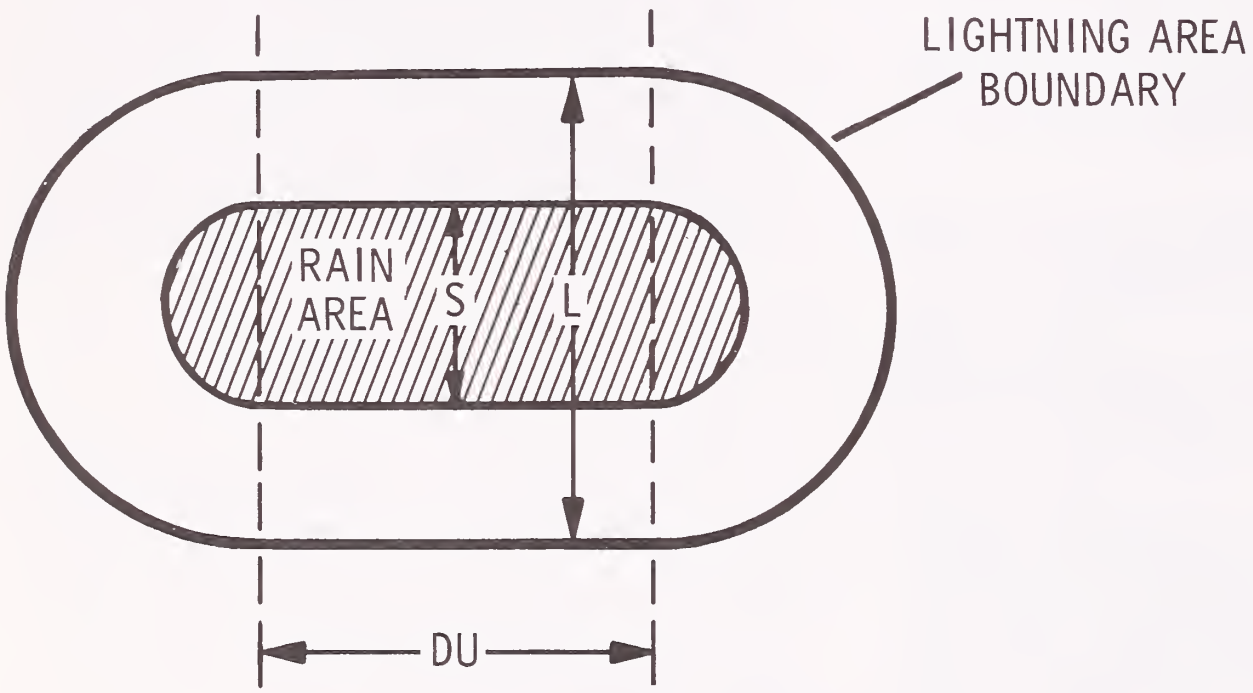

Figure 15.—Idealized shape of lightning and rain areas from a thunderstorm (from Fuquay and others 1979).

Table 13.—Storm characteristics by lightning activity level

Attribute	Lightning activity level					
	1	2	3	4	5	6
Cloud-to-ground discharge lightning strikes (strikes/2,500 mi^2)	0	12.5	25	50	100	N/A
Rain corridor length (mi)	0	3	4	5	7	N/A
Lightning corridor length (mi)	0	7	8	9	11	N/A

Simple geometry defines the fractional areas with (f_w) and without (f_o) rainfall:

$$f_w = (4s_d u_w s_s + \pi s_s^2)/(4s_d u_w s_{dl} + \pi s^2{}_{dl}) \quad (103)$$

$$f_o = 1 - f_w. \quad (104)$$

Fine fuel moisture (1-hour timelag) within the rain area is adjusted using a modified 1-hour timelag fuel moisture diffusion equation:

$$mc_{1r} = mc_1 + (d_{ef} - mc_1)(1 - \zeta \exp(-T/\tau)). \quad (105)$$

For 1-hour fuel, $1 = \zeta = \tau$; thus

$$mc_{1r} = mc_1 + (d - mc_1)(1 - \exp(-T)) \quad (106)$$

where

mc_{1r} is the fine fuel moisture in the rain area,
mc_1 is the computed 1-hour fuel moisture,
T is the storm precipitation duration ($T = p_d$), and
$d = (76.0 + 2.7p_d)$—see 10-hour fuel section.

Heat of preignition (eq. 76) is computed for the wetted area using ambient fuel temperature and mc_{1r} as independent variables.

Probability of ignition, P(I), and ignition component for the rain area (IC_I) are then computed from equations 80 through 84 as in the MCOI.

A weighted lightning ignition component (IC_W) is then computed using the rain fractional area and its associated ignition component (IC_I), and the nonrain fractional area and the IC computed for man-caused occurrence index (IC):

$$IC_w = [f_w(IC_I) + f_o(IC)]/100 \quad (107)$$

where both IC_I and IC are upwardly limited at 100.

If a general rain is noted on the fire-weather observation (or forecast), IC_W is set to zero.

LIGHTNING STRIKES

A cloud-to-ground (CG) lightning strike consists of several sequential events. In about 20 percent of these CG flashes an extended return stroke, or a "long continuing current" (LCC) is present. Fuquay and others (1967, 1972) have shown that this LCC stroke is highly likely to ignite most lightning-caused fires. Therefore, R_L is modified to include only LCC lightning events:

$$R_L = 0.20(S_{cg})(R_L)(K_1) \quad (108)$$

where

S_{cg} is the total number of lightning strokes, R_L is the local scaling factor, and

K_1 is a factor used to scale the predictions to strikes per million acres (model was developed on Nezperce and Clearwater National Forests in the Northern Region and $K_1 = 1.5$).

A second factor (K_2) is used to scale R_L such that when:

$LAL = 5$
$R_L = 1$
$K_1 = 1.5$
$IC_W = 100$

R_L will equal 100. Recalling that when $LAL = 5$, $S_{cg} = 100$, and including K_2, equation 108 becomes

$$100 = K_2(0.20)(100)(1)(K_1). \quad (109)$$

Solving for K_2 yields $K_2 = 5/K1 = 3.33$. Inserting these back into the R_L equation:

$$R_L = K_2(0.20)(S_{cg})(K) \quad (110)$$

yields the number of LCC discharges, per million acres, scaled to a local protection unit.

The lightning occurrence index is then calculated from:

$$LOI = [10R_L(IC_W)] + 0.25(LOI_y) \quad (111)$$

where

the multiplier 10 scales LOI to 100 when 10 fires per million acres are predicted,
R_L is the number of LCC discharges (locally scaled),
IC_W is the weighted ignition component, and
$0.25(LOI_y)$ is a persistence function to help account for carryover from the previous day's LOI (LOI_y).

The lightning risk scaling factor is empirically derived as follows:

$$K = \frac{10 \sum_{u=1}^{u=N} fires_u}{1.6 \sum_{u=1}^{u=N} LOI_u} \quad (112)$$

over a recent 3- or 4-year period. The K is then adjusted every 5 years:

$$K_{new} = \frac{10\ K_{old} \sum_{u=1}^{u=N} fires_u}{A \sum_{u=1}^{u=N} LOI_u} \quad (113)$$

where A is the rating area in millions of acres, and fires and LOI are as defined before except they are for later periods (see Deeming and others 1977 for more complete operational examples).

THE FIRE LOAD INDEX

The fire load index measures the total potential containment effort that may be needed on a given day. It combines the containment effort for a single fire (burning index), with the average number of expected fires:

$$FLI = \sqrt{(BI^2 + (MCOI + LOI)^2)}/1.41 \quad (114)$$

where the BI, and the sum of MCOI and LOI, are limited to a maximum value of 100. The normalizing factor of 1.41 limits the FLI to a maximum value of 100.

VARIABLES AND SYMBOLS

Variable	Description
A	Area (ft^2, m^2)
A_1	Age correction function for aging fuel sticks
$\overline{A}_i$	Mean total surface area of ith category per unit fuel cell
$\overline{A}_{ij}$	Mean total surface area of jth class and ith category per unit cell
$\overline{A}_T$	Mean total surface area per unit fuel cell
a	Age of fuel moisture sticks (days)
a_h	Y-intercept on live fuel regression
a_w	Y-intercept of woody fuel moisture regression
B	Secondary fuel stick aging function
B_I	Burning index (dimensionless)
b_h	Slope on live fuel regression
b_w	Slope of woody fuel moisture regression
C	Climate class dependent fuel stick aging function
C_c	1978 NFDRS climate class
D	Daily equilibrium moisture content boundary conditions for 100-hour fuel moisture computations, %
D_n	Period boundary moisture conditions for forecast 10-hour fuel moisture or 1,000-hour computations, %
d	Regional scaling factor (dimensionless)
d_o	10d
d_1	Man-caused risk scaling factor (dimensionless)
d_2	Correction for risk sources (dimensionless)
d_j	Unnormalized man-caused risk for the jth day of the week (number of person-caused firebrands/million acres)
EMC	Equilibrium moisture content, %
ERC	Energy release component (dimensionless)
f_i	Surface area weighting parameter I (dimensionless) ratio of surface area of ith category to total surface area, per unit fuel cell
F_L	Flame length (ft)
FLI	Fire load index (10 × number of fires/million acres)
F_o	Fourier number (dimensionless)
f_o	Fractional area of thunderstorm without rainfall
f	Fraction of herbaceous fuel to be transferred to 1-hour class
f_w	Fractional area of thunderstorm with rainfall
f_{ij}	Surface area weighting parameter II (dimensionless) ratio of surface area of jth size class to total surface area of ith category, per unit fuel cell
G_{ij}	Man-caused risk (number of firebrands) associated with the daily activity level
gu	Elapsed fraction of green-up period
H	Heat content (Btu/lb)
IC	Ignition component (dimensionless)

Variable	Description
IC_W	Rainfall area weighted ignition component (dimensionless)
I_R	Surface area weighted reaction intensity (Btu/ft^2-min)
I_{Re}	Load weighted reaction intensity (Btu/ft^2-min)
J	Julian date
K	Lightning risk scaling factor (dimensionless)
K_1	Lightning area scaling factor I (dimensionless)
K_2	Lightning area scaling factor II (dimensionless)
k_1	Drying or wetting factor in live moisture model
k_2	Temperature factor in live moisture model (dimensionless)
k_3	Calibration constant for computing P(I) (dimensionless)
k_4	Calibration constant for computing P(I) (dimensionless)
L	Length (ft, m)
LAL	Lightning activity level (dimensionless)
LOI	Lightning-caused occurrence index (number/million acres)
LOI_y	Yesterday's lightning-caused occurrence index (number/million acres)
MCOI	Man-caused occurrence index (man-caused fires/10^6 acres)
m_f	Fuel moisture content (fraction)
m_{fw}	Weighted "fine" dead fuel moisture (fraction)
m_x	Moisture of extinction, %
m_{xd}	Dead fuel moisture of extinction, %
m_{xl}	Live fuel moisture of extinction, %
mc	Ratio of characteristic fuel bed moisture content to dead or live fuel particle moisture of extinction
mc_h	Live herbaceous fuel moisture, %
mc_w	Woody fuel moisture content, %
mc_1	1-hour timelag fuel moisture content, %
mc_{10}	10-hour timelag fuel moisture content, %
mc_{10k}	Age-corrected fuel stick moisture content, %
mc_{100}	100-hour timelag fuel moisture content, %
mc_{1000}	1,000-hour timelag fuel moisture content, %
P(I)	Probability of ignition
P_1	Probability coefficient for P(I) calculations
P_2	Second probability coefficient for P(I) calculations
p_a	Daily precipitation amount (inches)
p_d	Precipitation duration (h)
p_{d1}	Precipitation duration for first forecast period (h)
p_{d2}	Precipitation duration for second forecast period (h)
p_r	Precipitation rate (inches/h)

VARIABLES AND SYMBOLS (con.)

Variable	Description
Q_{ig}	Heat of preignition (Btu/lb fuel)
Q_{ige}	Effective heat of preignition (Btu/lb fuel)
Q_{igmx}	Minimum heat for ignition (Btu/lb fuel)
R	Rate of fire spread (ft/min, cm/s)
R_1	Number of fire-starting lightning strikes in a rating class
R_L	Lightning-caused risk (number fire-starting strikes/million acres)
R_{MC}	Man-caused risk (man-caused firebrands/million acres)
R_{SRij}	Risk source ratio for man-caused risk sources for the ith source on the jth day
r	Radius (ft)
S_{cg}	Number of cloud-to-ground lightning strikes per 2,500 mi^2
S_e	Effective mineral content (lb silica-free minerals/lb ovendry fuel)
S_t	Total mineral content (lb minerals/lb ovendry fuel)
SC	Spread component (dimensionless)
SC_{max}	Maximum probable spread component (dimensionless)
SC_N	Spread component, normalized by maximum probable value (dimensionless)
s_d	Thunderstorm duration (h)
s_{dl}	Total storm length (with and without rain, mi)
s_s	Rainfall path length (mi)
s_1	Lightning area scaling factor I (dimensionless)
s_2	Lightning area scaling factor II (dimensionless)
T	Moisture stress simulation time step (h)
T_F	Fuel temperature (°C)
T_{ig}	Ignition temperature (°C)
u_w	Thunderstorm movement speed (mi/h)
V_b	Fuel bed total volume (ft^3, cm^3)
V_f	Fuel bed fuel volume (ft^3, cm^3)
V_v	Fuel bed void volume (ft^3, cm^3)
W	Dead-to-live loading ratio
W_f	Weight of fuel moisture sticks (g)
W_h	Total herbaceous fuel load (lb/ft^2; tons/acre)
W_{hg}	Load of herbaceous fuel that is still green (lb/ft^2; tons/acre)
W_{ij}	Net fuel load (for live fuels, i=2 and j indicates 1-hour, 10-hour, or 100-hour timelag class; for dead fuels, i=1 and j indicates 1-hour, 10-hour, or 100-hour timelag class)
W_n	Net fuel mass (total fuel mass less inorganic mass, lb/ft^2; tons/acre)
W_o	Total fuel mass (lb/ft^2; tons/acre)
W_{1h}	Load of 1-h prior to inclusion of herbaceous fuels (lb)
W_{1hd}	Total 1-hour load including dead herbaceous (lb/ft^2; tons/acre)
X_{1000}	Live fuel moisture recovery value, %
X_{y1000}	Yesterday's live fuel moisture recovery value, %
overbar	Mean value for any indicated variable

Greek Symbol	Description
α	Fraction of living fuel to dead in a fuel bed
α_d	Angle of daylight (degrees, converted to radians)
β	Packing ratio (dimensionless)
χ	Probability of ignition subfunction
χ_s	Fuel particle shape factor
δ	Fuel bed depth (ft, m)
δ_d	Angle of solar declination (degrees, converted to radians)
$\Delta\mu$	Potential moisture content change during stress period, %
$\delta\mu$	Actual moisture content change during stress period, %
Δmc_{1000}	24-hour change in the 1,000-hour moisture content, %
η	Moisture-damping coefficient for spread component
η_e	Moisture-damping coefficient for energy release component
μ	Relative moisture content, %
ν	Diffusivity (cm^2/s)
σ	Fuel bed porosity (dimensionless)
σ_L	Fire-weather station latitude (degrees)
σ_s	Slope factor
$\sigma\psi$	Wind factor
ϱ_b	Fuel bed density (lb/ft^3, g/cm^3)
ϱ_p	Fuel particle density (lb/ft^3, g/cm^3)
σ	Surface area-to-volume ratio (1/ft, 1/cm)
τ	Fuel particle timelag (h)
τ_r	Flaming residence time (min)
ζ	Timelag similarity coefficient (dimensionless)

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APPENDIX A: ORGANIZATION AND LOCATIONS OF NFDRS PROJECTS

The National Fire-Danger Rating System research work unit was organized in 1968 by the U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. It consisted of the following scientists: Mark J. Schroeder, project leader; Michael A. Fosberg, research meteorologist; and James W. Lancaster, forester.

In the spring of 1970, Schroeder returned to the fire meteorology project at the Riverside Fire Laboratory, Riverside, Calif. James W. Lancaster became project leader and John E. Deeming joined the project, relocating from the Southern Forest Fire Laboratory at Macon, Ga.

Other persons eventually involved included R. William Furman, meteorologist; David Rainey, forest resource technician; and Bruce McCammon, forest resource technician.

In 1973, Lancaster and Deeming relocated to the Boise Interagency Fire Center (BIFC), and in 1974 were joined by Robert J. Straub, computer specialist.

In 1975, the fire-danger research work unit was relocated under the Intermountain Forest and Range Experiment Station at the Northern Forest Fire Laboratory in Missoula, Mont. The research work unit was led by John Deeming, with assistance from research foresters Robert E. Burgan and Jack D. Cohen.

The 1971 NFDRS was initially tested on the following National Forest System units:

Arizona: Tonto, Gila, and Coronado National Forests.
California: Klamath National Forest.
Idaho: Boise National Forest.
Montana: Lolo National Forest.
New Mexico: Carson National Forest.
Wyoming: Medicine Bow National Forest.

Additionally, it was tested on the Chiricahua and Saguaro National Monuments in Arizona; the Shoshone, Idaho, District of the Bureau of Land Management; and finally, by the Georgia State Forestry Commission.

APPENDIX B: FUEL MODELS

Sections titled "Forest Fuels" and "Fuel Models" in the main text defined eight fuel parameters required to completely describe a fuel complex for fire modeling purposes. These parameters are:

1. H - heat content, Btu/lb,
2. π_p- fuel particle density, lb/ft^3,
3. S_t - total mineral content, %,
4. S_e - effective mineral content, %,
5. W_o - total fuel load, lb/ft^2,
6. δ - fuel bed depth, ft,
7. σ - surface area to volume ratio, l/ft, and
8. m_x - moisture of extinction, %.

The section titled "Spread Component" described the use of wind reduction factors used to reduce the 20-foot windspeed to the midflame windspeed required for solution of the fire spread model, and the section titled "Ignition Component" discussed the maximum probable spread component used in computing the ignition component. For calculating SC_{max}, each fuel model was run through the fire model with these parameter conditions:

1-hour fuel moisture	4%
10-hour fuel moisture	6%
100-hour fuel moisture	8%
1,000-hour fuel moisture	11%
Herbaceous fuel moisture	65%
Woody fuel moisture	75%
Windspeed (20-ft)	20 mi/h
1978 NFDRS slope class	1 (22.5% slope)
1978 NFDRS climate class	3

Table 14 delineates the physical attributes of the fuel models on the 1978 NFDRS.

Table 14.—Physical attributes of each of the fuel models on the 1978 National Fire-Danger Rating System

Attribute	Fuel Model																			
	A	B	C	D	E	F	G	H	I	J	K	L	N	O	P	Q	R	S	T	U
Load (tons/acre)																				
1-hour dead	0.2	3.5	0.4	2.0	1.5	2.5	2.5	1.5	12.0	7.0	2.5	0.25	1.5	2.0	1.0	2.0	0.5	0.5	1.0	1.5
10-hour dead	—	4.0	1.0	.5	2.0	2.0	2.0	1.0	12.0	7.0	2.5	—	1.5	3.0	1.0	2.5	.5	.5	.5	1.5
100-hour dead	—	.5	—	—	.25	1.5	5.0	2.0	10.0	6.0	2.0	—	—	3.0	.5	2.0	.5	.5	—	1.0
1,000-hour dead	—	—	—	—	—	—	12.0	2.0	12.0	5.5	2.5	—	—	2.0	—	1.0	—	.5	—	—
Woody	—	11.5	.5	3.0	.5	9.0	.5	.5	—	—	—	—	2.0	7.0	.5	4.0	.5	.5	2.5	.5
Herbaceous	.3	—	.8	.75	.5	—	.5	.5	—	—	—	.5	—	—	.5	.5	.5	.5	.5	.5
Surface-area-to-volume ratio (1/ft)																				
1-hour dead	3,000	700	2,000	1,250	2,000	700	2,000	2,000	1,500	1,500	1,500	2,000	1,600	1,500	1,750	1,500	1,500	2,500	2,500	1,750
10-hour dead	—	109	109	109	109	109	109	109	109	109	109	—	109	109	109	109	109	109	109	109
100-hour dead	—	30	—	—	30	30	30	30	30	30	30	—	—	30	30	30	30	30	—	30
1,000-hour dead	—	8	—	—	—	—	8	8	8	8	8	—	—	8	—	8	—	8	—	—
Woody	—	1,250	1,500	1,500	1,500	1,250	1,500	1,500	—	—	—	—	1,500	1,500	1,500	1,200	1,500	1,200	1,500	1,500
Herbaceous	3,000	—	2,500	1,500	2,000	—	2,000	2,000	—	—	—	2,000	—	—	2,000	1,500	2,000	1,500	2,000	2,000
Heat content (all fuels)																				
(Btu/lb)	8,000	9,500	8,000	9,000	8,000	9,500	8,000	8,000	8,000	8,000	8,000	8,000	8,700	9,000	8,000	8,000	8,000	8,000	8,000	8,000
Moisture of extinction (%)																				
Dead	15	15	20	30	25	15	25	20	25	25	25	15	25	30	30	25	25	25	15	20
Fuel bed depth (ft)	.8	4.5	.75	2.0	.4	4.5	1.0	.3	2.0	1.3	.6	1.0	3.0	4.0	.4	3.0	.25	.4	1.25	.5
SC_{max}	301	58	32	68	25	24	30	8	65	44	23	178	167	99	14	59	6	17	96	16

Constant fuel particle values for all fuels:

Fuel particle density (π_b):	32 lb/ft^3
Total mineral content (S_t):	0.0555
Effective mineral content (S_e):	0.01

APPENDIX C: EQUILIBRIUM MOISTURE CONTENT

Equilibrium moisture content (EMC) is an important aspect of the NFDRS dead fuel moisture models. The EMC is the moisture content (%) of a fuel particle allowed sufficient time to reach equilibrium with its environment (no net moisture exchange). EMC calculations are functions of temperature and relative humidity and are computed from regression equations developed by Simard (1968). Simard used tables from the Wood Handbook published by the U.S. Department of Agriculture, Forest Service, in 1955, revised 1974, as the basis for his equations. The equations for equilibrium moisture content are:

$$EMC = \begin{cases} 0.03299 + 0.281073h - 0.000578hT & h < 11 \quad \text{(C-1)} \\ 2.22749 + 0.160107h - 0.01478T & 10 < h < 51 \quad \text{(C-2)} \\ 21.06060 + 0.005565h^2 - 0.00035hT - 0.483199h & h > 50 \quad \text{(C-3)} \end{cases}$$

where

h is the fuel-atmosphere interface relative humidity (%),

T is the fuel-atmosphere interface temperature (°F), and

EMC is the fuel particle equilibrium moisture content (%).

APPENDIX D: WEIGHTING 24-HOUR BOUNDARY CONDITIONS BY DAY LENGTH

Latitude, date, and the earth's angle of declination in its orbit about the sun control day length cycles. In calculating the 100-hour and 1,000-hour fuel moisture, day length is used to weight the 24-hour maximum and minimum EMC's to compute the boundary EMC.

The day's maximum EMC is estimated from the minimum temperature and maximum relative humidity (assumed to occur simultaneously at night). Minimum EMC is computed from the day's minimum relative humidity and maximum temperature (assumed to occur simultaneously during the day).

These values are then weighted by the hours of either nighttime or daytime and averaged for the 24-hour period:

$$EMC_{24} = (h_d EMC_{max} + h_l EMC_{min})/24 \quad \text{(D-1)}$$

where h_d and h_l are hours of dark and hours of daylight, respectively. Hours of daylight are computed from station latitude and date of observation.

For the following discussion, refer to figure 16. The day's angle of solar declination (δ) is computed from:

$$\delta = (23.5)\sin(k(J - 82)) \quad \text{(D-2)}$$

where

J = Julian date
k = degree/day constant (0.9863 $\cong$ 1.00), and

23.5 is the maximum solar declination (at the solstices).

The distance from the polar axis to the circle of illumination is calculated from

$$Z = d(\tan \delta) \quad \text{(D-3)}$$

where d is the distance from the equator to the latitude circle defined by the station latitude (ϕ), and r is the radius of the earth:

$$d = r \sin \phi \quad \text{(D-4)}$$
$$S = r \cos \phi. \quad \text{(D-5)}$$

Thus

$$Z = r \sin \phi \tan \delta \quad \text{(D-6)}$$

and

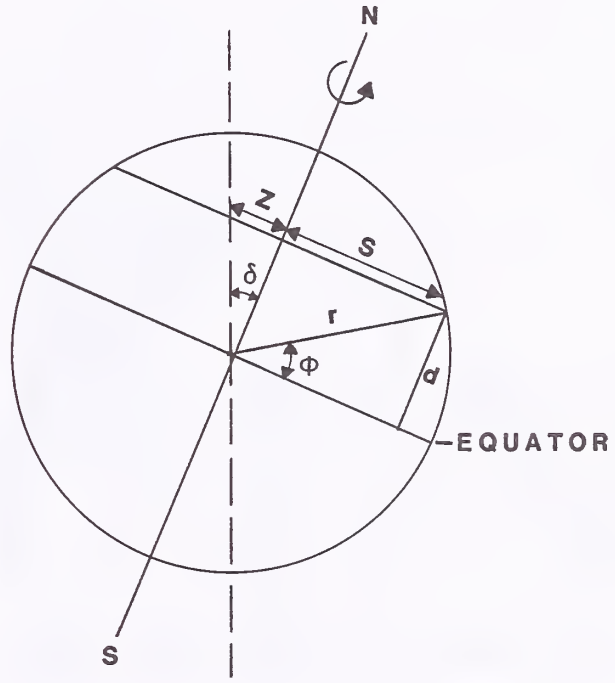
$$\alpha = \cos^{-1} (Z/S). \quad \text{(D-7)}$$

Substituting for S and Z

$$\alpha = \cos^{-1} \frac{r \sin \phi \tan \alpha}{r \cos \phi} \quad \text{(D-8)}$$

which simplifies to

$$\alpha = \cos^{-1} (\tan \phi \tan \delta). \quad \text{(D-9)}$$



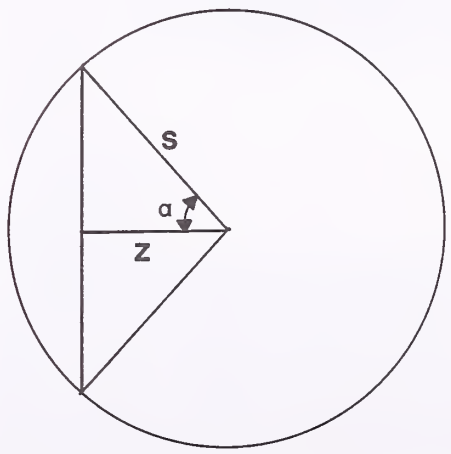


Figure 16.—Geometry for computing a day's angle of solar declination. The earth's axis is inclined 66.5° from the plane of orbit.

α is then proportional to day length. That is

$$h_1 = 24h - 2\,\alpha\,\frac{24h}{2\pi} \qquad \text{(D-10)}$$

where the angle measure is in radians.
Substituting for α, day length is

$$h_1 = 24h\,(1-(\cos^{-1}\,(\tan\,\phi\,\tan\,\delta))/\pi) \text{ in hours} \qquad \text{(D-11)}$$

Using the data from stations in Lytle Creek, Calif. (34° N), Libby, Mont. (48° N), and Fairbanks, Alaska (65° N), Burgan (1976) tested the effects of daylight) weighted boundary conditions on the MCOI, BI, and ERC indexes of the 1978 NFDRS.

Day length has little effect on MCOI and BI because they are most sensitive to the fine fuel moisture content as expressed through the spread component (used in computation of both the MCOI and BI). Here daily values affect the fine fuel moistures more than seasonal trends.

The ERC, on the other hand, is strongly influenced by the moisture contents of the heavier 100-hour and 1,000-hour fuels, which are affected by seasonal drying trends. Figures 17, 18, and 19 illustrate these differences.

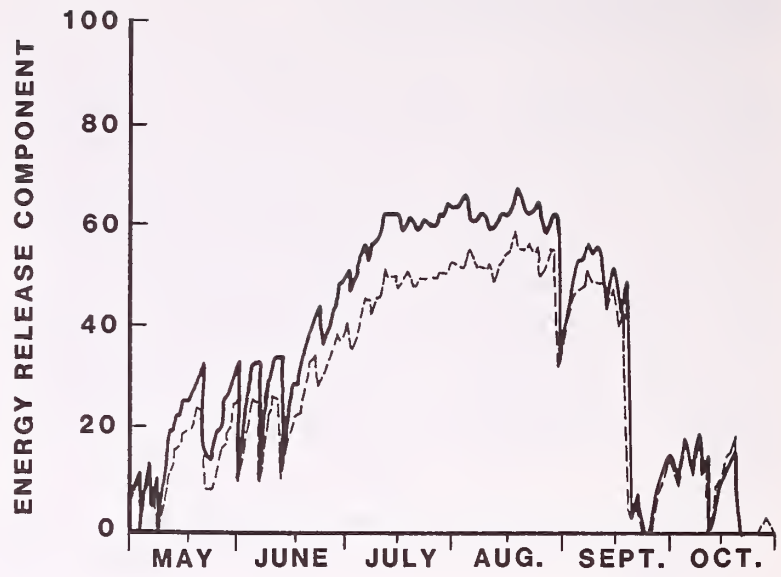


Figure 18.—Energy Release Component computed for Libby, Mont. (latitude 48° N, 1973 data), with a constant day length value (dotted lines) and with variable day length (solid line) (from Burgan 1976).

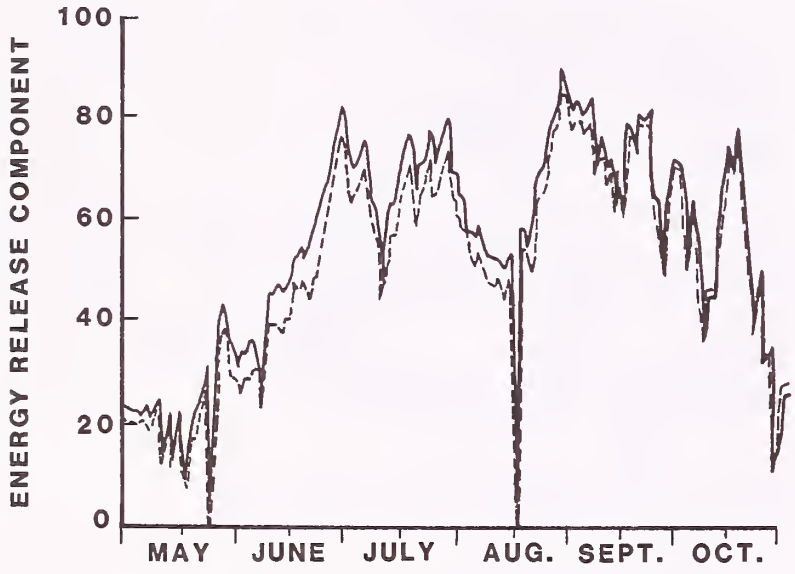


Figure 17.—Energy Release Component computed for Lytle Creek, Calif. (latitude 34° N, 1974 data), with a constant day length value (dotted line) and with variable day lengths (solid lines) (from Burgan 1976).

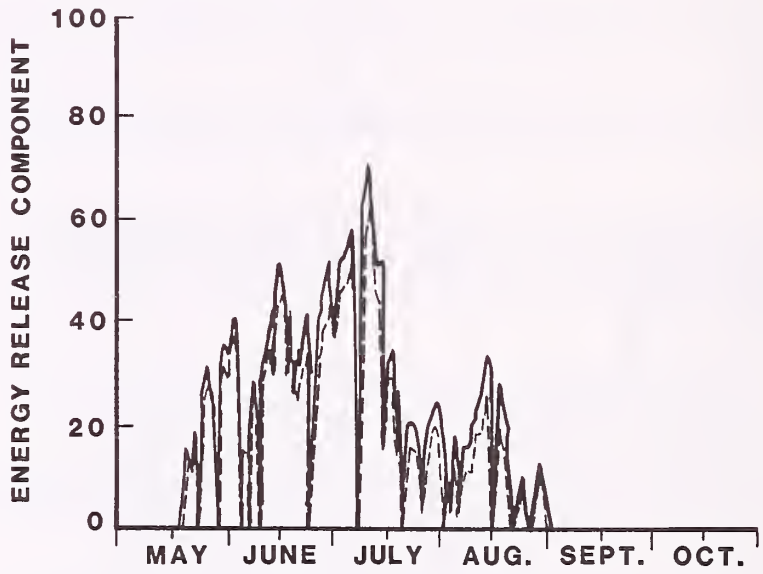


Figure 19.—Energy Release Component computed for Fairbanks, Alaska (latitude 65° N, 1975 data) with a constant day length value (dotted lines) and with variable day length (solid lines) (from Burgan 1976).

APPENDIX E: REFLECTIONS ON THE DEVELOPMENT, APPLICATION, AND FUTURE OF THE NATIONAL FIRE-DANGER RATING SYSTEM

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Introduction

Five years have passed since the NFDRS was updated (Deeming and others 1977). I remain interested in and am frequently consulted about the general subject of fire-danger rating and the NFDRS specifically. What follows are my views of the NFDRS—its technical adequacy, its use, and the obstacles to overcome to improve utilization of the 1978 or any future version of the System.

The NFDRS has some technical flaws. The development team was working against a deadline, and therefore utilized existing technology or the technology that could be developed in the time available. Our "best guess" prevailed when all else failed. I am convinced, however, that the usefulness of the System is not compromised by technological "splints", but by inappropriate application.

System Administration

NFDRS APPLICATIONS

Fire managers expected, and in most instances still expect, the NFDRS to provide the high spatial and temporal resolution of a fire behavior prediction system. Fire-danger rating areas are typically greater than 100,000 acres and the weather is observed and predicted for **one specific time** during the day at **one specific location.** Using this "worst case" approach reduces the uncertainty concerning the meaning of a rating derived from such a modest sampling effort.

Many decisions made at the different administrative levels of fire management have not been carefully analyzed and the requirements of supporting information have not been developed. Managers must recognize that the scale of the information used in making a decision must match the scale of that decision. The NFDRS was designed for low resolution, medium-to-large-scale applications; the Fire Behavior System (FBS) (Rothermel 1983) was designed for high resolution, small-scale application.

We must all recognize that managing wildfires is much more complex than when the NFDRS development program began. Managed fires, natural prescribed fires, delayed initial attack, economic efficiency, and cost-plus-net-value change were not everyday considerations in fire control offices in 1968. The scope of the modern fire management job requires new approaches for using weather and fire-danger ratings. Techniques for blending the NFDRS and FBS have not been developed. What has happened? The NFDRS has been frequently misapplied and has been used where it has failed to provide the high resolution information needed by management. Such failures have stimulated unjustified criticism and have undermined the credibility of the System.

PREPAREDNESS CLASSES

The bottom line of fire-danger rating in the day-to-day operation of a fire program is the manning class. This is sometimes called the manning and specific action class, preparedness class, adjustive class, or precautions class. The idea is to divide the continuum of fire danger into discrete classes to which preplanned management actions are keyed. The designations for the classes are commonly numerical, I (one) through V (five); or adjective, Low through Moderate, High, and Very High to Extreme.

The NFDRS does not include the procedures for delineating preparedness classes; the NFDRS produces numerical indexes of the fire danger. Manning class definition is the fire manager's job and one that has not been done satisfactorily in most instances.

Manning classes should be based on incremental needs for specific levels of suppression action. For instance, using wildfire reports (Yancik and Roussopoulos 1982) and historical fire danger (Furman and Brink 1975; Main and others 1982), it could be determined at what level of fire danger the probability of failure of initial attack with hand crews is unacceptably high. That level of fire danger might then be designated Class III, and a retardant aircraft preplanned for dispatch on Class III days. There is little hope the NFDRS or any updated version of the NFDRS will be satisfactory in the eyes of fire managers until the manning class problem is resolved.

TRAINING

The NFDRS is a flexible, adaptable system. If the user understands the NFDRS technology, the unique requirements of the myriad of agencies can be served and the evolving range of fire management tasks supported. The situation facing management is that a continuing effort must be made to train new personnel as the ranks of experienced NFDRS users thin over time.

Training is a continuing requirement for the proper application of NFDRS. The NFDRS is not like a bell buoy anchored to a reef. The requirement for the bell buoy to provide visual and audio warnings of a navigation hazard does not change; the requirements for the information the NFDRS is capable of producing are constantly evolving. Hence, up-to-date, knowledgeable users are essential

Technical

INPUT DATA

Weather

Without a program that assures uninterrupted, quality weather observations, the System will not work. Fischer and Hardy (1976) published an excellent guide for setting up and maintaining weather stations and making observations. If this guide were followed, and provisions made for taking data every day starting 30 days before the ratings are needed, many of the difficulties with the NFDRS would disappear.

A network of weather stations designed around the NFDRS would decidedly improve predictions. Until 1980, however, such a system was not feasible because instruments had to be located where people were available to read and record data. With the development of solar-powered, automatic instrumentation, and satellite communications (Warren and Vance 1981), the "people" limitation no longer exists. The issue of weather station network design is now timely and is being pursued at both Rocky Mountain and Pacific Southwest Forest and Range Experiment Stations, Forest Sevice, U.S. Department of Agriculture (Furman 1975; King and Furman 1976).

The higher the density of weather stations, the more accurate the fire-danger information. Because weather stations are expensive to set up and operate, the design must be cost effective. What information is vital to the decision making process? How accurate must the fire-danger information be? Network design guidelines would enable users to get the most for their money. This returns us to a subject already addressed, the requirement for fire management to systematize decisionmaking.

Fuel Models

Fuel model selection must be based on the capabilities of the model to emulate seasonal trends of fire potential in a fire-danger rating area. The suitability of a fuel model is a function of how well the fuel classes and the relative proportions of those classes in the fuel model match what is on the ground. If it can be shown that none of the 20 available fuel models are suitable, efforts to improve or develop new models should be considered.

Before building new fuel models, however, one should be certain that is where the fault lies. A new fuel model will not eliminate poor performance in situations where the NFDRS is being applied incorrectly or there exists an inadequate weather observation program. A great deal of art is involved in the development and evaluation of fuel models. Guidelines and a training program are needed for fuel model developers.

DERIVED INPUTS

Dead Fuel Moisture Models

The unrealistic indication of the recovery of fire danger after a precipitation event is a serious shortcoming of the NFDRS in areas where the primary fuel is litter and duff. Contrary to the assumptions made in the System, the atmosphere is not the only moisture source/sink (as determined by measurement of the ambient relative humidity, temperature, and precipitation). The soil and duff, after a precipitation event, are a significant source of moisture for dead plant material in the forest floor.

Another factor contributing to the overrating of fire potential in forested areas is the way the atmospheric data that drive the dead fuel moisture models are collected and interpreted. In the United States, fire danger has always been evaluated at open sites: the practice is consistent with the "worst case" approach to rating fire danger. This may be the time to introduce some flexibility into our fire-danger rating policy and use in-stand conditions where open areas are atypical. The Canadians have done this for years for forested areas.

Evidence that the current dead fuel moisture predictive models can be improved comes from Forest Service research units at East Lansing, Mich. (Loomis and Main 1980; Simard and Main 1982; Simard and others, in preparation), Seattle, Wash. (Ottmar 1980), and Tempe, Ariz. (Harrington 1982). Better NFDRS fuel moisture models would greatly benefit prescribed burning and the fire behaviour prediction and fire management planning systems. The NFDRS fuel moisture predictions are used in those applications because the NFDRS is the only weather "bookkeeping system" available. Improved dead fuel moisture models would be easily incorporated into the NFDRS, but one must be careful to assess the "bottom line" effects on the ratings (see section titled "System Tuning").

Live Fuel Moisture Models

The critical step in applying the NFDRS where the condition of the live vegetation dominates the fire danger is the proper keying of the System's live fuel moisture models when new growth commences (Burgan 1979). It is a stated requirement that the NFDRS computations start a month before green-up, but that it seldom done in areas with a mid- to late-summer fire season.

The importance of responsive, accurate, live fuel moisture increases as the ratio of live-to-dead fuels in the fuel complex increases. In open hardwood and conifer forests, brush and chaparral, and range vegetation types, the live-to-deal fuel ratio is high; hence, live fuel moisture predictions must at least parallel actual conditions. The current models do a reasonable job if green-up is triggered on time and if the temperature adheres to a typical seasonal pattern.

What happens when conditions, principally the temperature, do not follow the typical seasonal patterns? The models do not work. How well or how poorly the current NFDRS live fuel models work has not been documented except for a study conducted in the Northeast by the Forest Service research group at East Lansing, Mich. (Loomis and Blank 1981). It is my view that new models incorporating temperature are required.

The NFDRS provides the option for directly entering live fuel moisture values, bypassing the models. The flammability of chaparral is very much a function of the moisture content of the foliage. In California, therefore, for years fuel moisture has been directly sampled. Because a general model for predicting the moisture content of live plants is unlikely, a foliage-sampling program may be warranted where the condition of live plants is very important to fire-danger rating

Drought

The effects of the intermediate-term (up to 6 weeks) meteorological drought is reflected by the NFDRS in both the live and dead fuel moisture predictions. Introduction of the live fuel model to account for curing of live herbaceous vegetation, and the 1,000-hour timelag class for large dead fuels in 1978 ameliorated a shortcoming the 1972 NFDRS, but it did not eliminate the drought problem in those areas where organic soils or very deep duff and litter are found. For those regions provisions must be made to incorporate a measure of

long-term meteorological drought such as that developed by Palmer (1965) or Keetch and Byram (1968).

Midflame Windspeed

In the NFDRS, the factors used to reduce the 20-foot standard windspeed to the midflame height depend on the fuel model and range from 0.6 for the "open" fuels to 0.4 for the "sheltered" fuels. Albini and Baughman (1979) have provided a better set of reduction factors that range from 0.1 to 0.6.

A great deal of "noise" in the fire-danger ratings is caused by the literal use of windspeeds in the lower (non-significant) speed ranges. Wind varies tremendously from point to point and from time to time. Windspeed measured at one point at one time is not necessarily a reliable indicator of the wind over a large fire-danger rating area.

I recommend that all winds less than 10 mi/h be treated as a constant 6 mi/h. Why 10 mi/h for the cutoff? The reasoning is that winds less than about 10 mi/h are dominated by local effects such as differential heating (Albini and others 1982). Above that windspeed, the odds are good that the wind field is being dominated by a meso- or synoptic-scale weather process that can be described and predicted.

THE FIRE-DANGER RATING PROCESSOR

Moisture of Extinction

The moisture of extinction is the fuel moisture level above which a fire will not spread. In the NFDRS the moisture of extinction varies by fuel model, ranging from a low of 15 percent in annual grasses to 40 percent in southern pine litter. Those values are supported, in some cases by studies (Brown 1972; Sneeuwjagt 1974; Bevins 1976; and Sneeuwjagt and Frandsen 1977), but they have been established subjectively for most fuel models. The fact is that the moisture of extinction not only varies between fuel types but also within fuel types as the windspeed and slope change. Also, the moisture of extinction for the initial igition is lower than the moisture of extinction for a going fire because of the limited energy contained in the typical firebrand.

Weighted (Characteristic) Fuel Moisture

In the Rothermel fire spread model (Rothermel 1972), the heterogeneous fuel (more than one fuel class in a fuel complex) situation is addressed by using a weighting process to calculate, for instance, a characteristic surface-area-to-volume ratio for the fuel complex. In the NFDRS, the weighting for the Spread Component is done exactly as Rothermel (1972) does, using as the basis of weighting the proportions of the total surface area of all fuels contributed by the individual fuel classes. For the Energy Release Component, the weighting is based on the contribution of the individual class load to the total load of the fuel complex. Weighting by surface area causes fire behavior to be underrated when the larger fuels are dry enough to burn, whereas weighting by loading causes the fire behavior to be underrated when the larger fuels are too wet to burn. Weighting by loading was introduced in the 1972 NFDRS and retained in the 1978 NFDRS to increase the influence of the condition of the larger fuels on the rating in the upper range of fire danger.

Using the weighted fuel moisture causes unrealistic ratings when the 100-hour and 1,000-hour timelag fuels have moisture contents well above the fixed dead fuel moisture of extinction. Put another way, even though the fine and intermediate fuels are dry enough to burn and carry fire, the NFDRS says "zero" because the weighted average fuel moisture exceeds the moisture of extinction. Experienced fire managers know that a fire will burn through one fuel stratum without involving the other fuel strata. The NFDRS should reflect that behavior.

SYSTEM TUNING

If changes are made to any of the items I have mentioned, the System will have to be recalibrated. The 1972 and 1978 versions of the NFDRS were subjectively tuned to compensate for limitations remaining in the component models. How is that done? The final tuning is done by manipulating the fuel model parameters until the ratings properly reflect conditions for selected cases (a severe fire period and a benign fire period, for instance) Recall my comment that fabricating fuel models involves a great deal of art. What constitutes a proper rating of any situation is very, very subjective. We spent hundreds of hours with users adjusting fuel model parameters to cause the NFDRS ratings to match subjective, nonquantitative appraisals of case situations.

SYSTEM VALIDATION

Currently, there is no common measurement of any fire phenomenon to correlate with NFDRS ratings.

Don Haines and his coworkers at East Lansing will soon publish the results of an evaluation using (1) probability of a fire day, (2) probability of a large fire day (a day with one or more fires 10 acres and larger), (3) number of fires per day and (4) number of fires per fire day (Haines and others, in preparation). The results are encouraging and show that the Ignition Component and the Spread Component are highly correlated with those four measures of fire acitivity.

Most of the published work has been directed at validating components of the System such as the fuel moisture models (Simard and Main 1982; Simard and others, in preparation; Forsberg and other 1981; Harrington 1982; Loomis and Main 1980; Loomis and Blank 1981; Ottmar 1980). Much work has been done to evaluate the Rothermel spread model which is the basis of the NFDRS Spread Component (Andrews 1980; Bevins 1976; Brown 1972; Sneeuwjagt 1974; Sneeuwjagt and Frandsen 1977).

An effort is under way at the Northern Forest Fire Laboratory to develop software to access the Fire Report Library (Yancik and Roussopoulos 1981) and Fire Weather Library (Furman and Brink 1975) for comparisons similar to those done at East Lansing. The problem remains, however, that without an agreed-upon set of measures of fire phenomena and standard methods of analysis, it is impossible to determine how good the System is or how much proposed changes to the NFDRS would improve its performance.

SUMMARY

A technical revision of the NFDRS alone will not cure all the problems with the fire-danger rating programs. What is needed is a national program that will emphasize research in NFDRS application, management, and validation, and that will revise the System as required.

Piecemeal or regional revisions would be unwise because every modification requires an extensive checkout of the impact on System performance. It would be much more efficient if all the contemplated changes were made at once by one group. A research, development, and applications program would be appropriate for this task.

Training at the national, regional, and local levels is a continuing need and must be provided for. Fire management is constantly evolving. It takes knowlegeable, experienced people to redefine the role of NFDRS and to properly apply the System.

Fire management is a demanding and increasingly complex job. The need to especially good decisionmaking is increased by the high cost of wildfire suppression and the forces that must be available to do the job. If properly supported and implemented, the NFDRS can contribute to efficient fire management.

☆U.S. GOVERNMENT PRINTING OFFICE: 1984-0-776-032/10,501

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The Intermountain Station includes the States of Montana, Idaho, Utah, Nevada, and western Wyoming. About 231 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

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